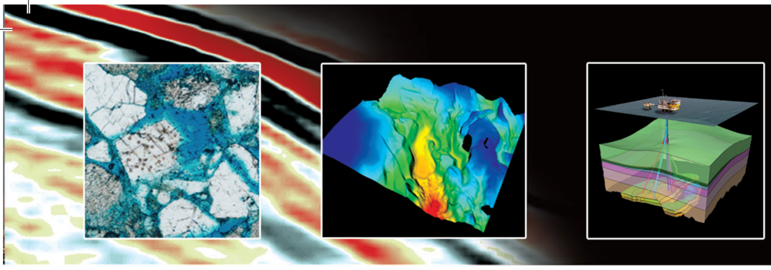

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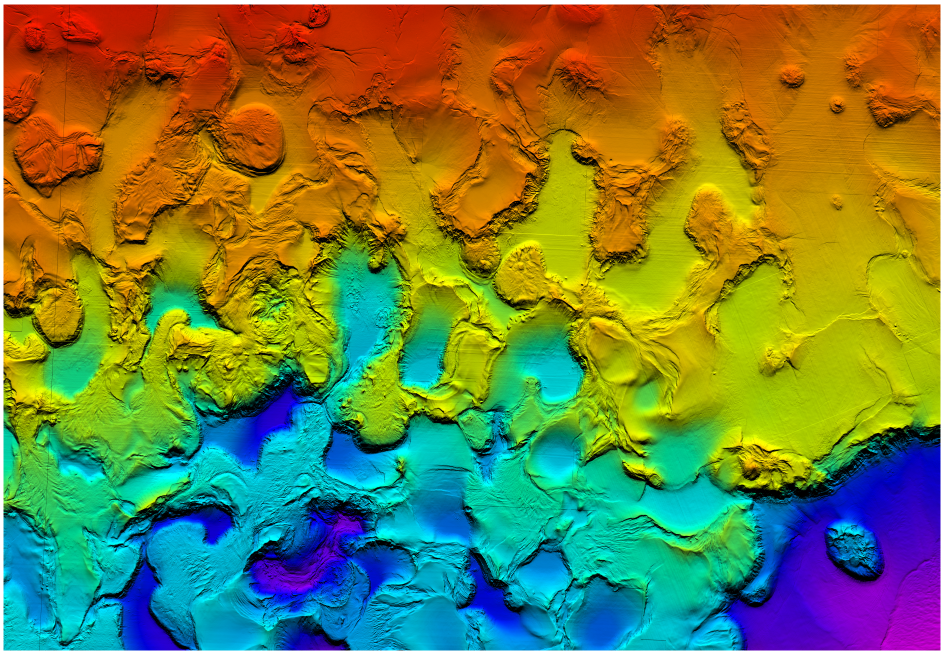
Salt Tectonics:

Understanding Rocks that Flow

29-31 October 2019

The Geological Society, Burlington House, Piccadilly, London



PROGRAMME AND ABSTRACT BOOK

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Salt Tectonics: Understanding Rocks that Flow

29-31 October 2019

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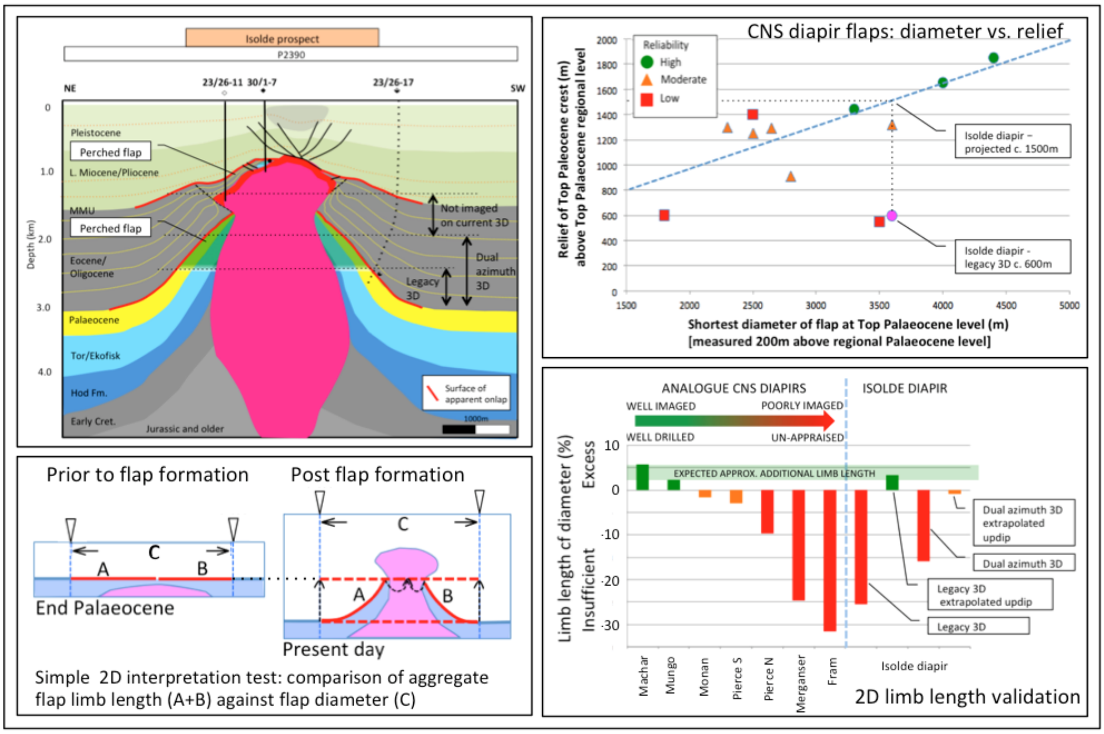
Day One: Session One – Regional North Sea

The Isolde prospect: predicting trap relief in the CNS diapir perched flap play

Graham Goffey
Soliton Resources Limited

This talk will discuss the structural geometry of the Cretaceous and younger cover of salt diapirs in a UK Central North Sea study area. These diapirs pierce through Palaeocene stratigraphy and host commercial hydrocarbon fields in a package of Palaeocene sandstone and Cretaceous chalk that is interpreted to have been originally deposited on the diapir crest. This former cover sequence typically now displays a 'perched flap' geometry some way below the crest of the diapiric salt body. Seismic processing with inappropriate salt/velocity models can compromise the imaging of steeply dipping flank strata (e.g. Merry et al, 2014). The study was undertaken to allow prediction of the structural relief of a diapir perched flap reservoir in Blocks 23/26e and 30/1d, in order to determine whether a viable exploration target had been overlooked on poor quality legacy 3D.

A systematic review of published literature on diapirs within the study area permitted the recognition of typical structural geometries on better quality 3D and allowed some older structural interpretations to be ruled out. To a first order, these diapirs share a common, late-stage structural history involving Late Cretaceous to Miocene down-building followed by rapid Plio-Pleistocene sedimentation, which blanketed the diapirs. Phases of active diapirism due to slight contraction occurred during the Early Eocene, Mid Miocene (Davison et al, 2000) and Pleistocene (Goffey et al, 2018). An alternative structural model (e.g. Carruthers et al, 2013) invoking earlier salt piercement and large-scale Miocene contractional shortening to develop structural relief at top Palaeocene is considered unlikely.



Differential sedimentation during Eocene to Miocene down-building is shown to be the first order control on structural relief at top Palaeocene (top perched flap) level, with condensed crestal sediments thickening down-flank to a regional thickness of around 1500m. A second-order control is flap limb length (in a 2D sense), which essentially reflects the diameter of flap strata above un-deformed, regional level, modified by the degree of symmetry of salt piercement. Longer limbs (larger diameter flaps) can develop greater structural relief during down-building than can shorter limbs (smaller diameter). Consequently, top Palaeocene flap relief above regional level can be shown to be directly proportional to flap diameter at top Palaeocene level. Reflecting a causal mechanism, this relationship was utilised to predict the presence and to estimate the trap relief of a diapir flap trap named the Isolde prospect. Poor quality legacy 3D data image some 600m of top Palaeocene relief above regional level however the calibrated diameter-relief relationship predicted a total relief of some 1400m - 1500m, implying that around 800m - 900m of relief were not being imaged on legacy 3D.

A 2D comparison of the aggregate top Palaeocene limb length with the top Palaeocene diameter at regional level allowed a simple interpretation validation, in effect comparing the length of the deformed (present-day) and un-deformed limbs. This simplified approach has several inherent limitations but broadly confirms the flap interpretation and provides interesting insights when a number of CNS diapirs are compared. Radial extension, as demonstrated by mapped concentric faulting, suggests that these diapir flaps have been extended in the dip direction and indeed well imaged, extensively drilled diapir flaps show aggregate limb lengths slightly greater than the un-deformed diameter. Several flaps with up-dip appraisal wells but moderate quality 3D imaging show aggregate limb lengths comparable to or slightly less than the diameter, implying that most but perhaps not all of the limbs are imaged. Finally, several diapir flaps unconstrained by up-dip drilling show substantial limb length deficits, suggesting that seismic data are not imaging the full extent of these under-appraised traps. This was the case with the Isolde prospect on legacy 3D. However, extrapolating the flap up-dip to the expected relief gave limb lengths in line with expectations and thus provided some validation of this reconstructed but largely un-imaged trap geometry. The presence of a large, mostly un-imaged, exploration prospect was inferred.

Modern dual azimuth 3D data covering the Isolde prospect was purchased and interpreted after license award. This dataset suffers from the processing pitfalls mentioned above and is thus considered capable of substantial improvement. Nevertheless these data image an additional 400-500m of the predicted 800-900m of trap relief and thus a good portion of the expected flap. These data are being re-processed during 2019 to mature the Isolde prospect towards exploration drilling.

This study allowed the identification of an overlooked prospect in a well-drilled part of the Central North Sea. It sheds light both on the controls on trap geometry in the perched flap play and on flap evolution, which may have wider implications.

NOTES:

Fault inversion and salt tectonics: structural development of the Lindesnes Ridge, Central North Sea

Hugh Anderson, Andreas Høie, Per Erik Overlie, John Berry, Paul Charles Reid, Wayne Oxborough, Vilde Nesbo Bakke, Vegard Dahl-Eriksen.
Aker BP, Jåttåvågveien, Stavanger, Norway

The Lindesnes Ridge, located in the Norwegian Central Graben, is a ca. 25 km long, NW-SE trending inversion anticline that hosts the prolific Valhall, Hod and Eldfisk oil fields. The structure has previously been presented as a case study for salt tectonics in a setting influenced by basement-involved extension, shortening and associated fault inversion. Here, an updated interpretation of regional 3D seismic data and integration of well data reveals the extent of structural heterogeneity along the ridge. These data are used to present a model of the interaction of salt tectonics and fault inversion around the Valhall and Hod fields (Fig. 1).

During the Permian, Zechstein evaporites were deposited within the isolated Feda Graben, which underlies the present-day Lindesnes Ridge. Subsequent Jurassic rifting reactivated pre-existing faults, including the western-bounding Skrubbe Fault Zone and the parallel Mode Fault Zone (Fig. 1.), offsetting and burying the Zechstein deposits. Continued extension and normal faulting coincided with or initiated salt withdrawal, resulting in the deposition of anomalously thick Upper Jurassic and Lower Cretaceous hanging wall packages. The evacuated salt synchronously flowed up the hanging wall of the Skrubbe Fault in the south and to the Mode diapir in the north. The region experienced shortening during the Late Cretaceous and Palaeocene, reactivating the normal faults as reverse structures, inverting the Jurassic synrift and remobilizing the Zechstein salt. Deposition of Hod and Tor Formation chalks, which form the principal oil reservoir, occurred during the initial phases of inversion and folding. The nature of structural development has resulted in an inverse relationship between the thickness of Lower Cretaceous deposits versus Upper Cretaceous chalks.

Mapping indicates that shortening was accommodated by a range of inversion styles depending on the geometry of the pre-existing Skrubbe Fault Zone and the presence of salt. Moreover, the work indicates that the Skrubbe Fault Zone is comprised of a series of relays and splays which form a Palaeozoic horst that separates the Feda Graben from the adjacent Lower Cretaceous Ål Basin (Fig. 1). To the southeast, where the horst is widest, salt withdrawal and subsequent shortcut faulting resulted in complex minibasin geometries which partly overlie the Palaeozoic high (Fig. 2a). Under the Hod Field, well control indicates that the salt remained high during the Mesozoic and may have formed an active diapir during shortening. In contrast, the centre of the structure, under the Valhall Field, is almost devoid of salt and is likely the point of greatest early Mesozoic salt withdrawal. Here the amplitude of the inversion anticline is greatest and shortening above the Skrubbe Fault Zone is accommodated by shortcut reverse faults which propagated into the Ål Basin (Fig. 2b). To the north, where the Ål Basin is absent, both the Skrubbe and Mode Fault Zones were reactivated, with limited salt movement and no evidence of shortcut faulting.

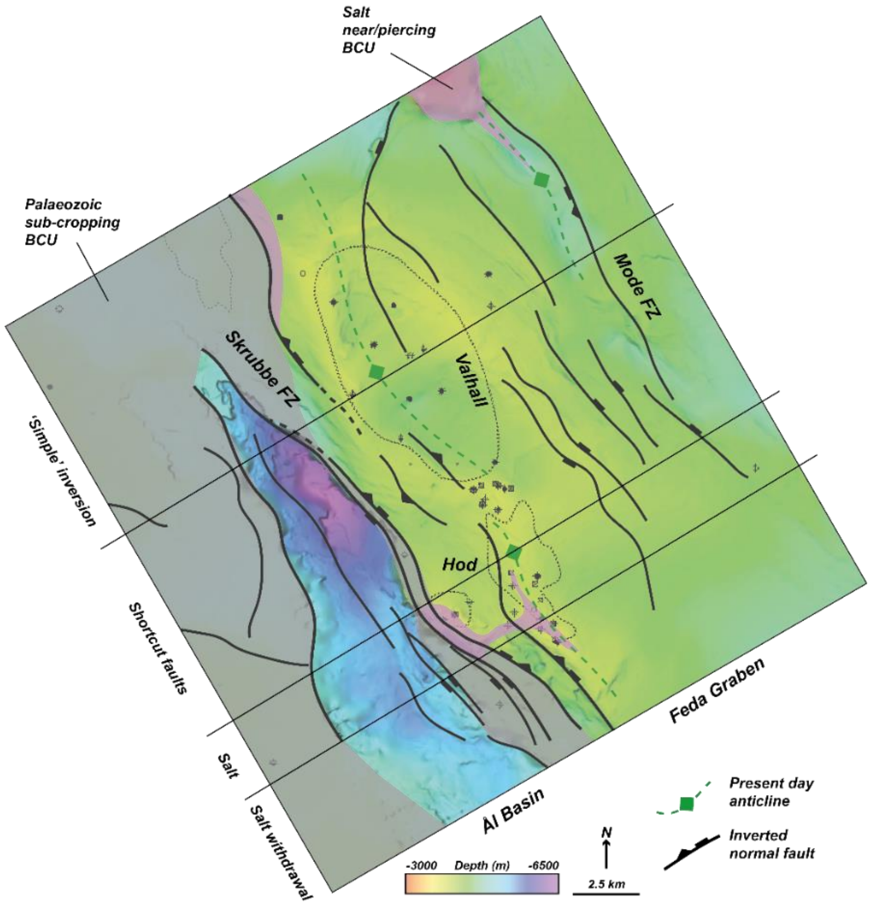


Figure 1. BCU depth structure map showing main faults, and the distribution of remobilised salt under the Lindesnes Ridge. The map has been divided into domains based on the style of inversion accommodated by the Skrubbe Fault Zone.

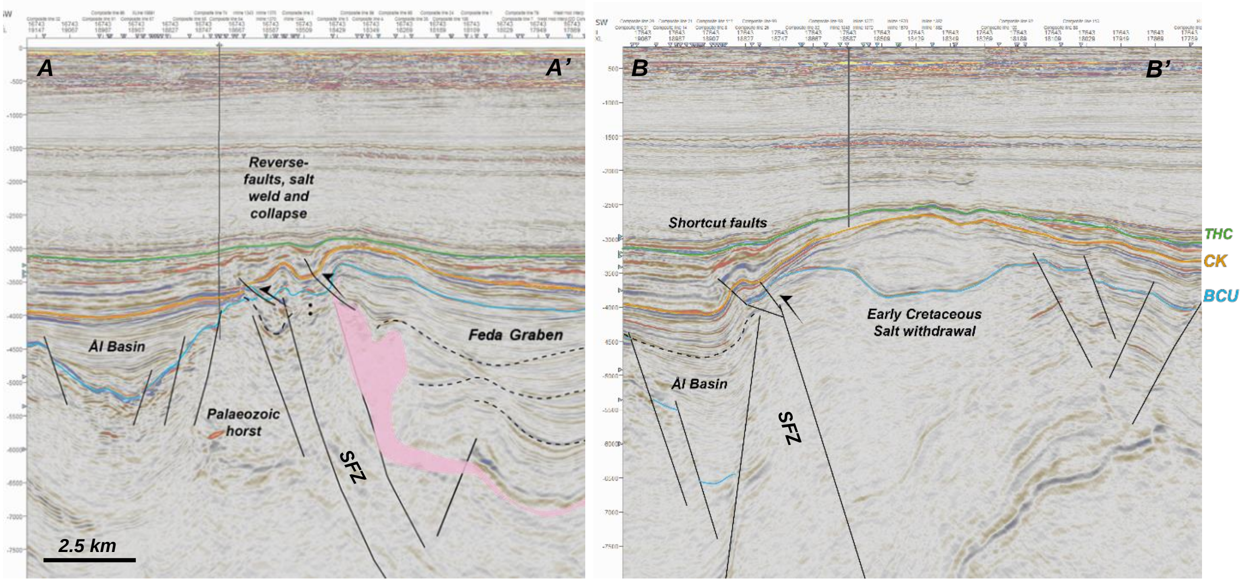


Figure 2. Depth seismic sections illustrating the difference in structural geometries along the Skrubbe Fault Zone (SFZ) between a) the south and b) the north of the Lindesnes Ridge. THC; Top Hard Chalk, CK; Top Cromer Knoll, BCU; Base Cretaceous Unconformity. V.E:1.5. Data is courtesy of PGS (MC3D-CGR2015M-KPSDM).

NOTES:

Salt-Sediment interactions during the tectonic evolution of the Southern Permian Basin, Offshore Netherlands

Jade Metcalfe
University of Leeds
2018 MSc Structural Geology with Geophysics Graduate

A detailed study on the salt-sediment interactions offshore of the Netherlands has been carried out, with a focus on their underlying relationship with the tectonic evolution of the Southern Permian Basin.

Through the analysis of 42 high-quality regional 2D seismic lines, a comprehensive structural understanding of the study area has been established. This allowed for the identification of salt mobilisation, spatial variation in salt structures throughout the area and the driving mechanisms of salt movements.

Findings suggest three major phases of salt movement within the Netherlands sector of the Southern North Sea, with regional tectonic events inducing mobility:

1. (i) Post-orogenic extension (237Ma), following the formation of Pangea initiated initial Zechstein movements within the Triassic, which effected the near-entirety of the study area.
2. (ii) Extension within the Dutch Central Graben during the break-up of Pangea (152Ma) later induced a second mobility phase in the Late Jurassic, with extensive salt migration and salt wall formation along graben margins.
3. (iii) During the Alpine Orogeny (66Ma), Late Cretaceous inversion of the Broad Fourteens Basin reactivated pre-existing salt structures, resulting in tall, piercing diapirs in the central sector, and salt pillows forming extensive salt cored anticlines in the south.

Regional tectonics in the Southern Permian Basin have not only induced salt movement through displacement loading, but also via gravitational loading in the creation of accommodation space for sediments. Thus, outlining the fundamental governance tectonics have on salt mobilisation.

Zechstein movements are vital with regards to petroleum systems in the Netherlands offshore area. The findings of this study should be considered and built on during future research of the area (potentially aided by three-dimensional data) to better understand potential targets in an exploration setting.

NOTES:

Relationships between pre-salt and post-salt fault systems and salt structural trends in the Southern North Sea basin

Anna D. Preiss, Jürgen Adam
Department of Earth Sciences, Royal Holloway University of London, Egham, UK

The Southern North Sea basin is a part of the Southern Permian Basin. Here the Zechstein evaporite sequence separates the pre-salt Paleozoic basement from the Mesozoic-Cenozoic post-salt basin fill and acts as a basin-wide viscous detachment partly decoupling the tectonic deformation above and below the salt. Salt tectonic processes in the basin are driven by two contrasting mechanisms, firstly, regional tectonic thick-skinned deformation of the basement rocks and, secondly, gravity-driven thin-skinned deformation of the post-salt overburden. The degree to which either of these processes dominates in a certain area of the basin, can be studied qualitatively in terms of regional fault distribution patterns and quantitatively by analysing the orientation of faults and salt structures. This study attempts to compare regional pre-salt and post-salt structural patterns together with salt structural trends in the Southern North Sea both qualitatively and quantitatively in order to better understand the interplay between basement-involved and gravity-driven salt tectonic processes at a basin scale.

Dataset and methodology

The seismic dataset used in this study is a subset of the regional 3D Southern North Sea Megasurvey basin-scale 3D seismic dataset provided by Petroleum Geo-Services (PGS) containing 40 3D seismic volumes, covering a total area of over 61000 km. Fault networks were mapped on two regional horizons: 1) top of the Paleozoic pre-salt section and 2) 50 ms above the top of the Zechstein (Upper Permian) evaporite layer, using similarity and ant tracking attributes (computed in Kingdom and Petrel software packages respectively). The ant track raster maps were spatially referenced in ArcGIS and detected discontinuities traced to create pre-salt and post-salt fault maps. These fault maps were then 1) overlain and compared visually to delineate areas of fault trend correlation (Fig. 1, right) and 2) analysed for fault orientation on rose diagrams (Fig. 1, left). Salt structural trends, obtained by tracing centrelines of mapped salt structures, were also analysed and compared with pre-salt faults (Fig 1, left).

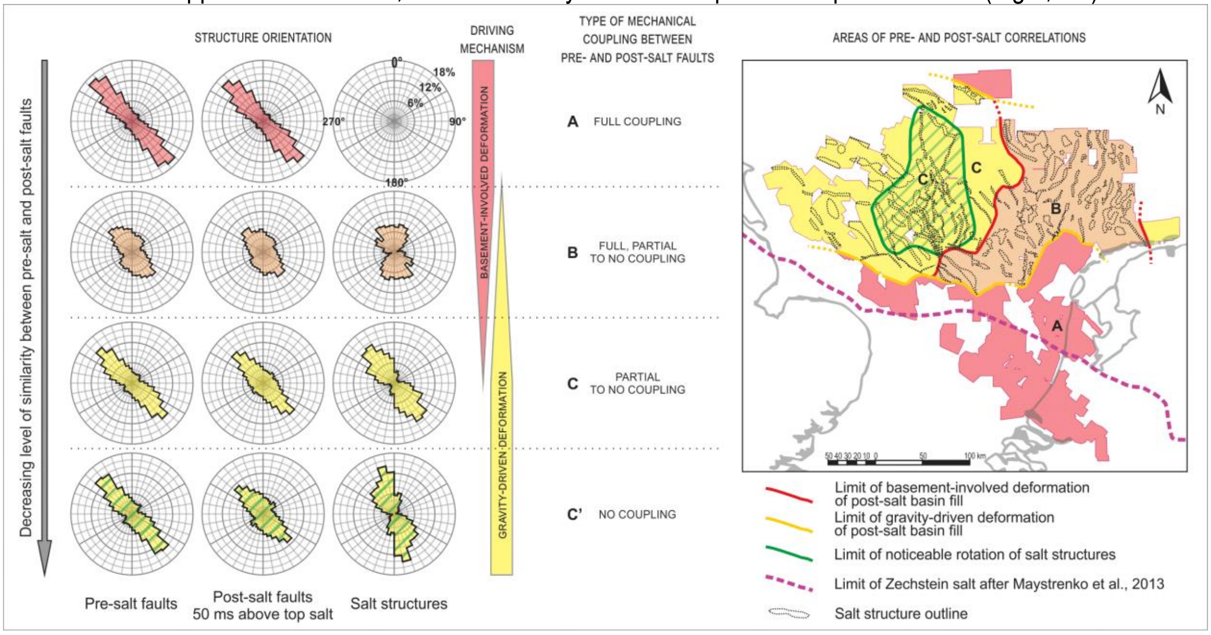


Figure 1: Fault orientation analysis. Left: rose diagrams showing regional variations in orientation of pre-salt faults and post-salt faults detected 50 ms above the top of salt horizon and salt structures. Right: map showing characteristic areas with different levels of basement control and degree of gravity-driven processes on the deformation of the post-salt basin fill. Areas were delimited based on similarity between pre-salt and post-salt fault patterns and using seismic cross-sections. Salt structure outlines are shown by black dotted lines.

Results and discussion

Regional fault orientation analysis reveals a high similarity between the pre-salt and the post-salt sections. Both fault populations have a weakly bimodal distribution, with the dominant NW-SE direction and the secondary SW-NE direction, implying a strong mechanical link between the pre-salt and post-salt structures in general. Three different types of pre- and post-salt fault correlations, that can be mapped in different areas of the basin, were identified (Fig. 1, right): A. Strong correlation, predominantly basement-involved deformation, thin and undeformed salt, B. Medium correlation, area of Upper Jurassic rifting with mostly basement-involved deformation and gravity-driven deformation around salt structures. Thick, deformed salt, salt structures mostly aligned with main basement faults, C. Medium to weak correlation, predominantly gravity-driven deformation. Thin to thick salt, salt structures partly rotated oblique to basement structures. Additionally, a subgroup of C was isolated to highlight the area of a noticeable rotation of salt structural trends, C’. Fault orientation analysis performed for all three correlation types shows that:

- As evident from Fig. 1, the dominant NW-SE direction of the basement structures characterizes areas A, C and C’ but is strongly suppressed in area B. This area, characterized by dominance of the Upper Jurassic Central Graben rift, shows an increased share of NE-SW and N-S trends.
- The dependence of post-salt structural trends on pre-salt structural trends decreases with an increasing importance of gravity-driven processes (Fig 1, left).
- Salt structural trends are correlated with basement structural trends in the area of basement-involved deformation, where salt structures are present.
- A rotation of c. 30° towards the N-S orientation of NW-SE and NE-SW trends can be observed for salt structures with respect to the pre-salt faults underneath (Fig. 2) indicating gravity-driven transport of the post-salt overburden from W and E directions into the basin centre with regional E-W shortening and N-S stretching (pure shear) of the overburden in Area C’

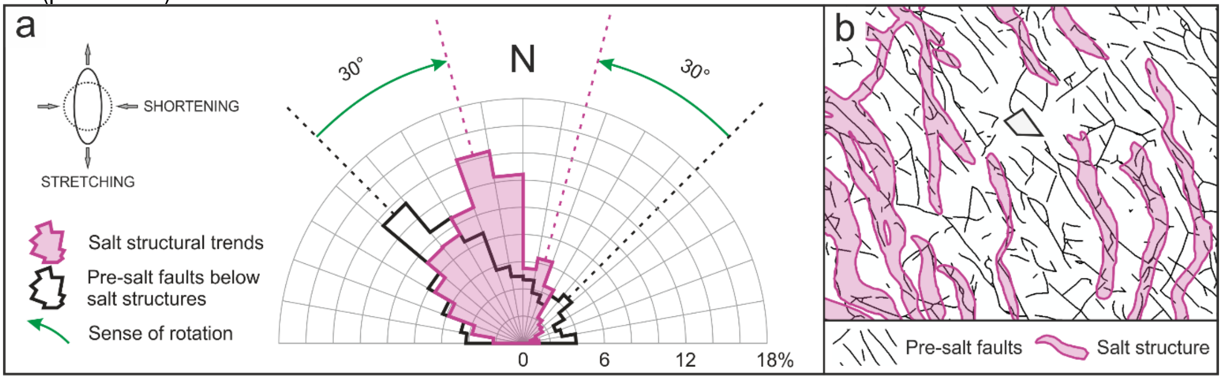


Figure 2: a) Rose diagram showing salt structural trends overlain on pre-salt faults in area C’ (Fig. 1), b) Fragment of area C’ (location in Fig.1), characterized by a noticeable rotation of salt structural trends with respect to underlying pre-salt faults.

Conclusions

Analysis of pre-salt and post-salt fault patterns and orientations allowed to define and map out three types of fault correlation, which can be translated in simple terms into types of mechanical linkage between fault systems above and below salt: A. Strong correlation, full mechanical coupling in area of thin, undeformed salt, B. Medium correlation, all types of coupling present; thick salt and Central Graben rift dominance, C. Medium to weak correlation with predominantly no mechanical coupling on thin to thick deformed salt. A noticeable rotation of salt structural trends in area C’ implicates a gravity-driven transport of the post-salt overburden towards the basin centre (pure shear mode). Further studies are required to better understand the effect of other factors, such as salt thickness, changes of basement slope and amount of fault displacement on the post-salt fault systems and salt structure orientation in the Southern North Sea basin.

NOTES:

Kinematics of multi-stage salt diapirs in the Southern North Sea

Gerardo Gaitan, Jürgen Adam
Royal Holloway University of London

The Southern North Sea (SNS) is part of the Southern Permian Basin containing a several km thick Zechstein megahalite sequence. Today's SNS structural framework is the result of Mesozoic rifting controlled by Paleozoic structural elements and gravity-driven salt tectonics leading to the widespread formation of salt structures (Fig.1). The Mesozoic sub-basins in the SNS contain numerous examples of complex salt diapirs reflecting various salt-kinematic stages related to halokinetic and regional tectonic phases of basin evolution which are documented by their synkinematic sedimentary sequences. These multi-stage diapirs are characterized by complex geometries and fault-fracture networks. A better understanding of the evolution of multi-stage salt diapirs and their associated structures is important for the energy sector because salt diapirism creates complex trap geometries and associated fault structures lead to widespread compartmentalization of reservoirs and hydrocarbon traps.

We use the supra-regional high-resolution Southern North Sea 3D MegaSurvey seismic dataset, provided by Petroleum Geo-Services (PGS), for the systematic analysis of a multi-stage salt diapirs in the Southern North Sea. We utilized Two Way Travel Time (TWTT) structure maps, isochron maps and similarity attribute maps to analyze the multi-stage evolution of salt diapirs in the different sub-basins of the SNS. Here, we present a detailed study of a prominent salt wall (A1) located in the Broad Fourteen basin focusing on its complex Mesozoic evolution (Fig.2).

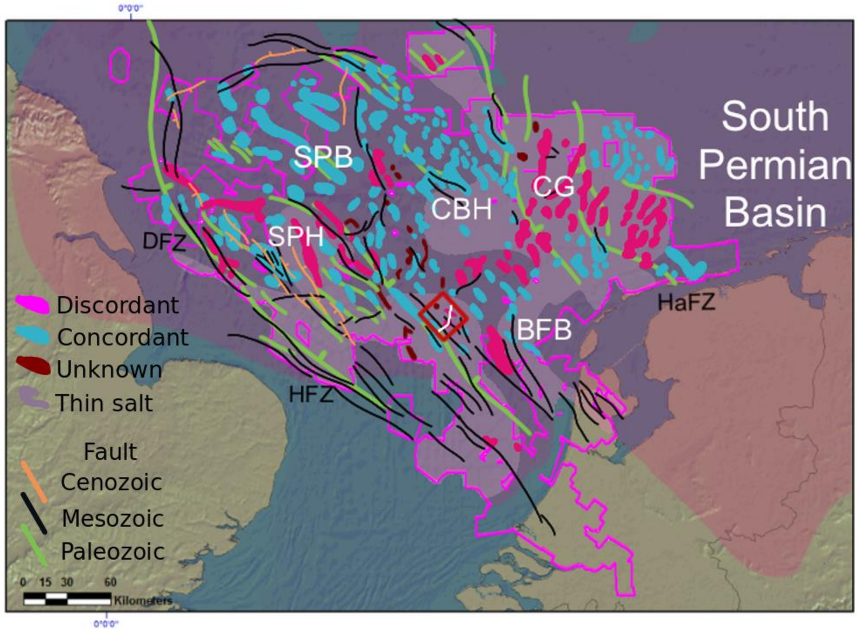


Figure 3. Simplified structural map of the Southern North Sea and South Permian Basin, adapted from Glennie (1990), Evans et al., (2003) and Doornenbal and Stevenson (2010). Pink outline represents 3D PGS MegaSurvey dataset. Lighter pink represents thinner salt <300ms today. SPH=Sole Pit High, SPB=Silver Pit Basin, CBH=Cleaver Bank High, BFB=Broad Fourteens Basin, DFZ=Dowsing Fault Zone, HFZ=Hewett Fault Zone, HaFZ=Hantum Fault Zone, CG=Central Graben. Red inset location of AOI and seismic line.

The isochron maps show thickness variations of syn-kinematic halokinetic depositional sequences in depocenters near salt diapirs documenting timing of salt mobilization and directions of salt flow. Similarity attribute maps display fault and larger fracture sets related to salt diapirism and its relationships to halokinetic or regional tectonic processes. The salt wall A1 is located in the Broad Fourteens Basin, a NW-SE positive trending inverted intra-continental basin (Fig.1). Top Zechstein TWTT structure maps highlight two salt-structural trends, both trending NW-SE. Within the AOI, up to five salt structures can be identified.

The salt wall A1 is an 8.4 km long and 1.2 secs tall salt structure. Graben structures and normal faults at Triassic levels delineate the extent of the salt wall A1 highlighted by attribute similarity maps displaying low similarities (Fig.2a). Moreover, Triassic isochron maps, show no thickness variations on either side of salt wall A1 during the Triassic indicating a pre-kinematic layer (Fig.2a,b). The Base Cretaceous Unconformity (BCU) horizon is used to analyze structural features at the underlying Jurassic levels (Fig.2c). The BCU TWTT structure map shows that Jurassic sediments are only preserved near salt wall A1 and adjacent salt structures. Similarity maps show minor faulting, and mostly, younger

Cretaceous-age faults cutting through Jurassic sediments. The BCU-Top Triassic isochron map shows that depocenters shifted closer to the salt wall A1, and that different depocenter geometries developed on both flanks of salt wall A1 (Fig.2a,c). Synkinematic sediments are observed steepening on the eastern flanks of salt wall A1. Here, the depocenter-axis tilts away from the salt structure as expected to see in a halokinetic active stage (Fig.2a). The continuous Top Cretaceous TWTT structure map covers the salt wall A1. Figure 2a shows that the salt wall A1 had a positive relief during the Cretaceous where younger sediments onlapped on the top of the diapir. Similarity maps highlight a slightly different structural orientation trending NW-SE (Fig.2a,d). The Top Cretaceous-BCU isochron map show a thin sedimentation at the carapace of salt wall A1 (Fig.2d). Lastly, intra-Cenozoic sediments display concentric-collapse structures at the carapace of salt wall A1.

In conclusion, the salt wall A1 went through at least 4 different diapiric stages. The salt wall started as a reactive diapir due to E-W extensional stresses during the Late Triassic – Early Jurassic. The initial salt wall had a total length of about 26km but sediment loading and differential salt flow compartmentalized the salt wall. During the Jurassic, differential and syn-halokinetic sedimentation reveal a halokinetic stage of active diapiric rise, where salt was being mobilized into the salt wall from the adjacent east and south-east mini-basins. A positive relief during the Cretaceous was created by contraction and resulting diapir rise due to the Alpine Orogeny. Concentric faulting evidence diapiric collapse post-kinematically during the Paleogene-Neogene transition.

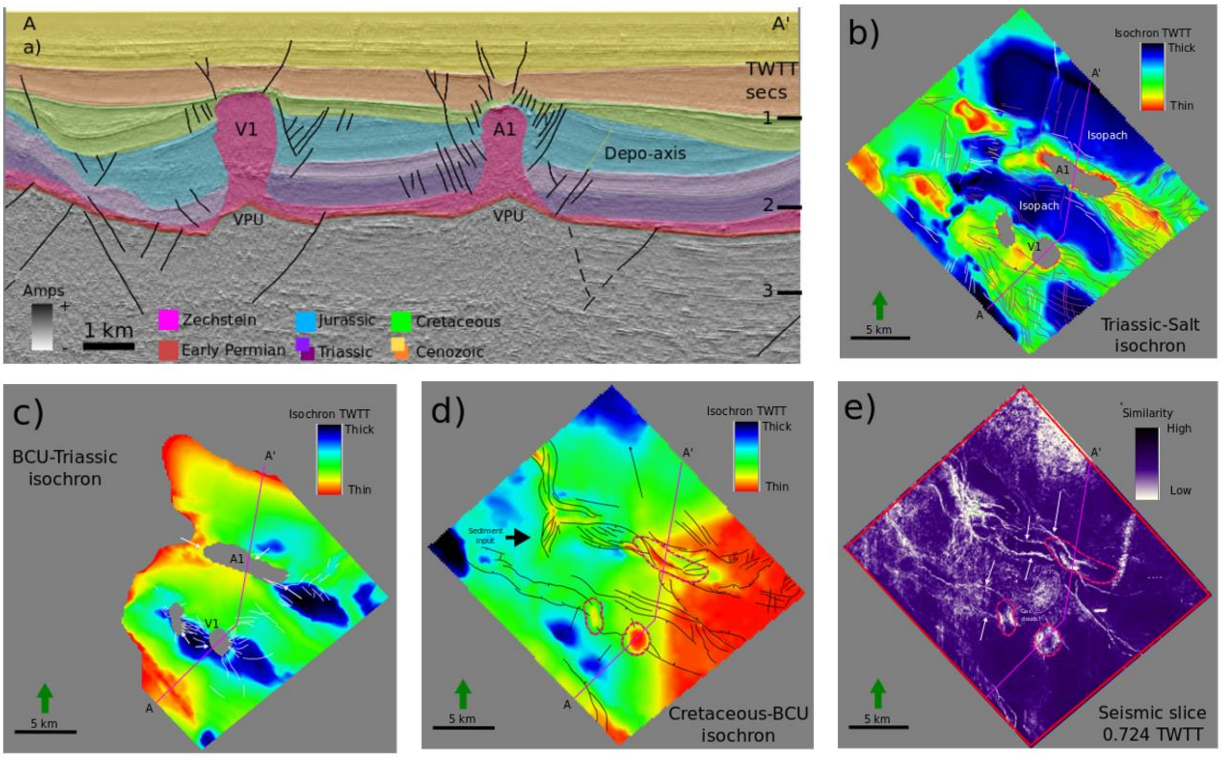


Figure 4. a) Cross-section visualizing salt diapir V1 and salt wall A1. b) Top Triassic-Top Salt isochron with structural features from Early and Late Triassic levels. c) BCU-Top Triassic isochron highlighting Jurassic sedimentation and Jurassic structural features only. White arrows indicate salt mobilization promoting diapiric rise. d) Top Cretaceous-BCU isochron with Cretaceous faults. Outline of buried diapirs also shown. Black arrows show shift of basins away from the salt structures. e) Similarity attribute map at 0.724 secs TWTT. White arrows show collapse structures due to salt migration. Outline of buried diapirs also shown.

NOTES:

Day One: Session Two – Regional – Europe

KEYNOTE: Remnant allochthonous salt in the fold and thrust belt of Haute Provence

Rod Graham[1], Samuel Brooke-Barnett[1], Adam Csicsek [1], Naïm Cellini[2], Jean-Paul Callot[2], Lidia Lonergan[2], Jean-Claude Ringenbach[3]
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Structural discontinuities that represent withdrawn allochthonous salt bodies (welds that were once salt glaciers on topographic surfaces) are being documented more and more now that fundamental salt research has told us what to look for on seismic. It is not usually simple. Even on passive margins and in petroliferous salt basins with exceptional seismic data, such structures can pass un-recognised or may be argued about.

In fold and thrust belts which have developed from salt basins and salt bearing passive margins the evidence is commonly even more difficult to see. It requires a very thorough understanding of the fold and thrust geometry (less and less appreciated these days) and the ability to see through that deformation, as well as a fundamental appreciation of the stratigraphy and the sedimentary environment.

We believe that we have evidence that a number of these structures formed at different times in the development of the passive margin and the later thin-skinned fold and thrust belt that make up the sub Alpine chains of Haute Provence. The allochthonous evaporites in question (now gypsum, but presumably originally containing salt) are of Triassic age but evidence of their presence or former presence can be seen throughout the Mesozoic and Tertiary section in Haute Provence (Fig 1).

Graciansky, Dardot, Mascle, Gidon and others described salt diapirism in Haute Provence and Alpes Maritimes many years ago but did not recognise the allochthonous element. At the time they worked such things were barely recognised for what they are, much less for what they were. We are more fortunate now. The Sigsbee glacier in the Gulf of Mexico is very well known and can serve as a model, and onshore equivalents have been recognised, for example in the Sivas basin of Turkey (Legeay et al 2018).

Several years ago Graham, Jackson, Pilcher and Kilsdonk suggested that the reduced overturned section of Liassic and Middle Jurassic forming a cliff (the Barre de Chine) above the village of Barles in Haute Provence might be a flap above a one-time salt extrusion onto the Oxfordian sea floor. They recognised that the salt has welded out or been eroded away since then but postulated that during its history it may have provided the detachment surface on which the Digne nappe was emplaced.

The Barre de Chine may be the biggest but is by no means the only such structure in Provence, and its Oxfordian age is not unique. The Astoin Flap (near Motte du Caire, north of Digne) is probably also associated with salt extrusion onto an Oxfordian topographic surface, but the double verging flap on the Teillon mountain and the Chasteuil structure (both near Castellane), together with the many isolated Tithonian lenses (lentils) scattered throughout Provence must be younger, most likely earliest Cretaceous. An intensely compressed upright isocline (a squeezed-out diapir) exposed near the hamlet of Gevaudan (Fig2), is an mantled by a highly reduced Mesozoic section, but around it there is evidence of salt extrusion onto both Oxfordian and an Albo-Cenomanian topographic surfaces and not far away, along the Var river near Daluis the base of an outcropping gypsum body still lies parallel to bedding within the Albo-Aptian black shales for half a kilometre or so along strike.

Evidence of allochthonous salt was not confined to the Mesozoic. A section an anomalously thick, steeply dipping Eo-Oligocene Marnes Bleues (pelagic marls succeeding the Nummulitic limestone in the foreland basin sequence in Provence) can only be explained by salt evacuation in Eocene time on an allochthonous canopy that must have accumulated on a late Cretaceous. topographic surface. The geometry seems to be analogous with the Roho systems of the Gulf of Mexico, but here it is developed on a secondary canopy with salt ultimately evacuated along a major strike-slip fault. A remnant of it is still preserved at Daluis. The St Benoit Marnes Bleues accumulation is therefore a secondary minibasin. Again, it is not the only one. The well-known Miocene basin of the Velodrome north of Digne is almost certainly a salt related minibasin which developed by sinking into a salt glacier. The difference here is that this particular salt glacier must have been expelled over an Oligocene land surface beyond the front of the Authon Nappe (an earlier part of the Digne Thrust system). The setting is thought to be analogous with the Salt Range in Pakistan, extruded from beneath the frontal Potwar thrust.

Salt is most likely to extrude over a topographic surface when the rate of expulsion is faster than background sedimentation, so it is no surprise that most of the postulated salt glaciers of Haute Provence coincide with periods of pelagic shale deposition (Oxfordian, Albo-Cenomanian). The Early and Late Cretaceous canopies presumably equate with high stands in the Early and Late Cretaceous, but we cannot prove it. The Salt Range analogue for the Velodrome also remains a hypothesis.

NOTES:

Compressional salt tectonics in the inversion of a rifted margin: field case studies from the South Pyrenean fold-and-thrust belt and insights from 2D numerical modelling

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Triassic Keuper evaporites have long been recognized as the main detachment level for thrusting in the Pyrenean fold-and-thrust belt. The deformed Late Cretaceous to Eocene foreland basins of the Pyrenees show evidence of diapirism that has been often overlooked due to the more obvious imprint of thrusts and fault-related folds. We reinterpret a classic transect of the Southern Pyrenees (Noguera Ribagorzana river transect, figure 1), exploring the variation of the salt-tectonics structural style and addressing the role of halokinesis in the structural and sedimentary development of the basin.

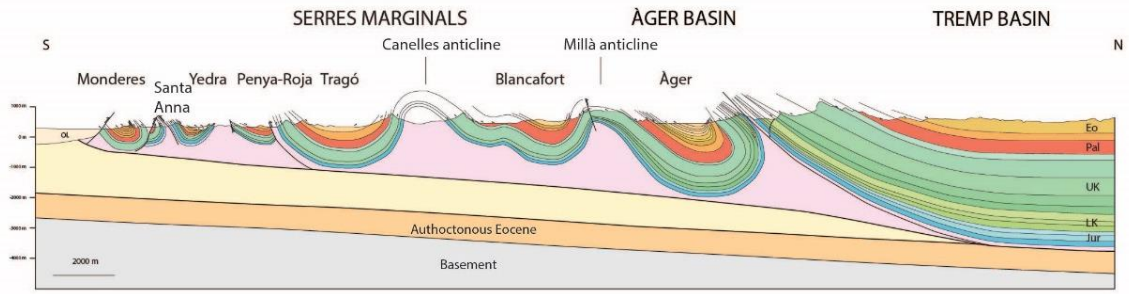

Figure 5

According to our interpretation, the study area contains precursor diapirs that started developing during the Mesozoic pre-orogenic extensional episode of the Pyrenees, and areas where the halokinetic movements were likely triggered during the Pyrenean compression.

Our study focuses in three areas where the role of halokinensis has been assessed:1) The Sierras Marginales foothills, a system of polygonal salt ridges and intervening synclines filled with early synorogenic sediments that now appear intensely imbricated. 2) The Montsec thrust and Ager basin, which we reinterpret as a linear salt wall and an adjacent synclinal depocenter with a long history dating back to the extension, subsequently squeezed during the orogeny. 3) The Pobla de Segur and Serra de Gurp intramontane conglomerates, deposited during the late Eocene and Oligocene on top of the Mesozoic overburden and the Keuper evaporites. Their unusual dip direction, opposed to the paleocurrents, suggests a syn-depositional tilting of the basin, probably related to salt extrusion across the salt walls exposed north of the basin.

Our field observations lead to fundamental questions regarding the relative roles of buckling and drape folding by salt migration in this foreland belt, as well as the mechanisms that facilitated the transition from early salt-cored folding to late thrust imbrication.

We have used 2D to address two main questions: 1) The role of pre-existing diapiric structures and the pre-compressional thickness of the salt in the deformation styles (figure 2).

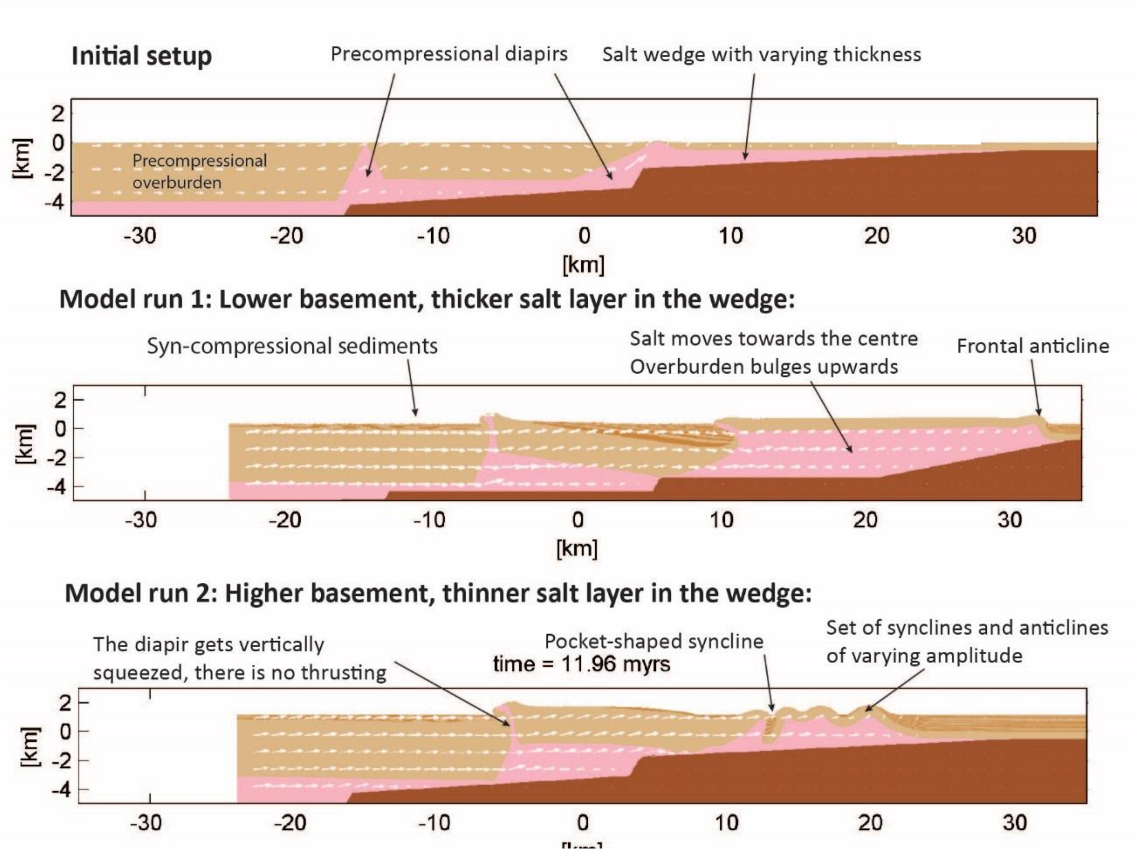

Figure 6

2) The role of erosion in distributing the sedimentary loads and equilibrating the thickness of the different basins, thus affecting its buoyancy above the evaporite layers.

The results emphasize the importance of the salt-to-overburden thickness ratio and differential sedimentary loading in controlling the final geometry of folding, its sequence and timing, and also in producing backstops for thrust propagation. In the cases with a high evaporite vs overburden layer thickness ratio, there is less number of folds forming because of the quick bulging of the area. The effect of syntectonic sedimentation is not enough to counterbalance the upwards push of the evaporites. In the cases with a thinner evaporite layer there is a balance of the upwards push of the evaporites, the buckling by compression and the downbuilding by syntectonic sedimentation, so a series of anticlines and synclines can develop. The wavelength and amplitude of the folding varies from one fold to another due to the presence of a thick evaporite layer.

NOTES:

Influence of salt tectonics on the subalpine chains of SE France under extensional, strike-slip and compressional regimes

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The influence of salt tectonics in the development of passive margin settings has been increasingly recognised over the past decade thanks to advances in seismic acquisition and interpretation in the North Sea, Gulf of Mexico, offshore Brazil and West Africa. This increase in understanding has resulted in the recognition of salt related deformation structures in outcrop within fold and thrust belts. The Subalpine Chains of SE France represent an example due to the presence of Triassic evaporites. In the Mesozoic the area was located on the European plate margin during Early Jurassic Tethyan rifting and subsequent Middle Jurassic to Middle Cretaceous thermal subsidence.

Field mapping and section construction and restoration was done between the towns of Castellane and Guillaumes. A major NE-SW trending strike slip fault zone, the “Rouaine-Daluis Fault System”, running through this region has undergone approximately 6.4 km of sinistral displacement since the Oligocene. The strike slip zone marks a major regional structural boundary, separating two dominant structural trends either side of the fault zone (Figure 1). Deformation along the Rouaine-Daluis Fault System can be roughly divided into a transtensional regime in the northeast, and a transpressional regime in the southwest.

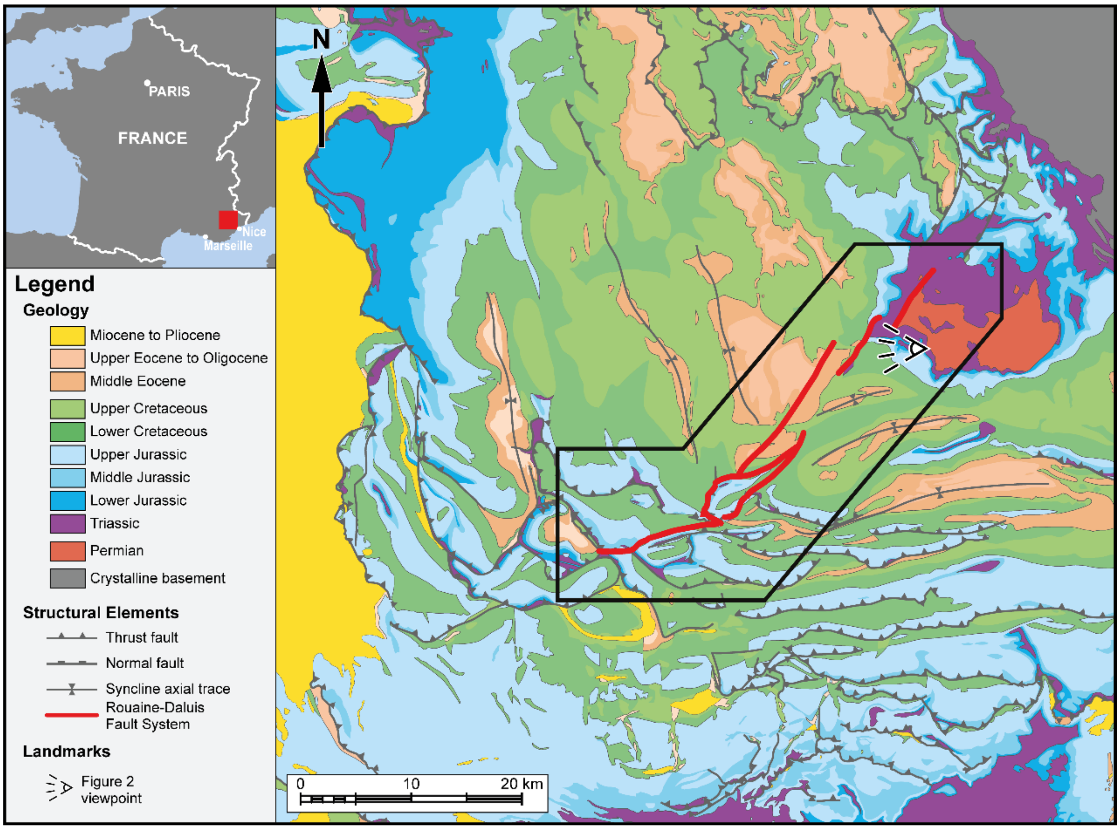

Figure 7 Geological map of the subalpine chains of SE France showing large scale structural trends, and the extent of the study area (black box).

Evidence for reactive diapirism during Tethyan rrifting can be observed in the Northwest of the field area, off the flank of the Permian Dôme de Barrot. Here, the Triassic Muschelkalk and Kuyper are repeated or intensely folded, yet unconformably overlain by the lower Jurassic. Within the lower to middle Jurassic stratigraphy there are slumps, thickness changes, and onlap of bedding directly onto Triassic gypsum.

Halokinesis was not limited to the rifting phase of European margin development however, and synsedimentary deformation is evident in the Upper Jurassic to Cretaceous passive margin section throughout the field area. Along the Rouaine Daluis Fault System, out of place Triassic gypsum bodies are observed in direct contact with Jurassic to Middle Cretaceous units. Bedding relationships between this allochthonous Triassic gypsum and Aptian-Albian shales suggest that a salt wall trending parallel to the Fault System was exposed at the sea floor as a salt canopy during the Middle Cretaceous (Figure 2).

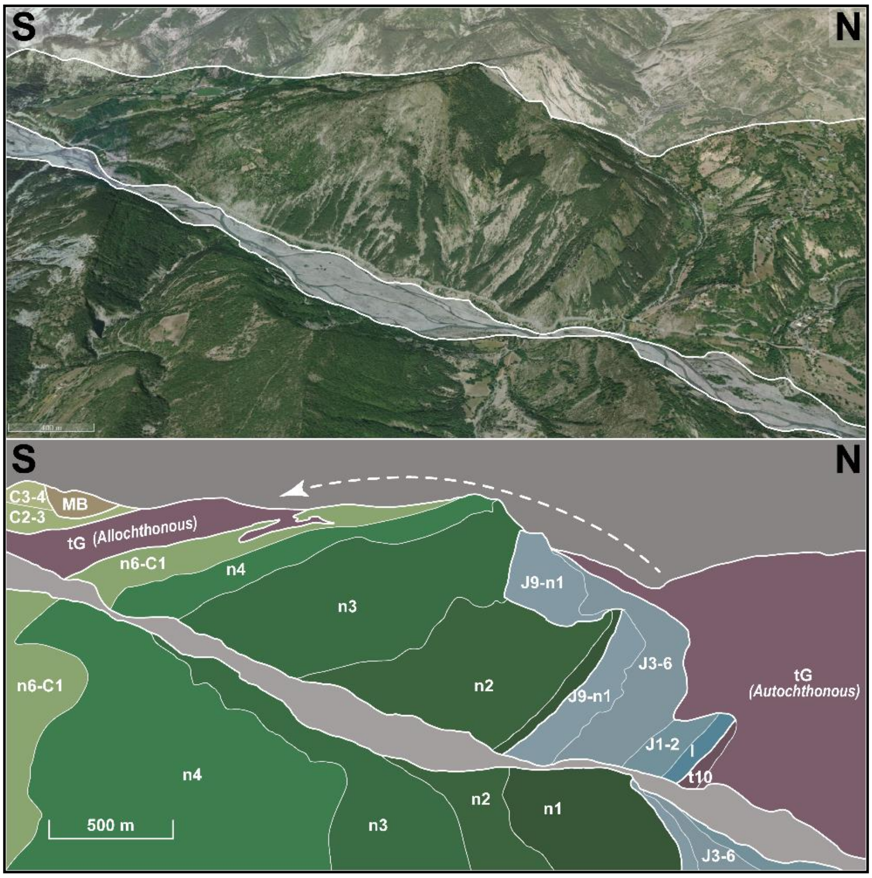

Figure 8 Top: Viewpoint overlooking western bank of Var river, acquired from www.geoportail.gouv.fr/carte. Bottom: Geological interpretation showing overturned Jurassic (blue), change in dips in Cretaceous (green), and both autochthonous and allochthonous Triassic gypsum.

Under Cretaceous to Oligocene alpine compression, the relatively weak salt layers provided décollement horizons, and preexisting salt diapirs and walls would have absorbed lateral strain as the evaporites were preferentially squeezed out to surface. Thickness changes and folding in Eocene to Oligocene units along the Rouaine Daluis Fault System suggest that strike slip faulting may have initiated along a preexisting salt wall.

Halokinesis has evidently been influential on the tectonic evolution of the Subalpine Chains since evaporite deposition in the Triassic, and the resulting salt structures were critically oriented for sinistral strike-slip faulting during Alpine shortening.

NOTES:

The effects of salt tectonics in the evolution of a fold and thrust belt, Southern Subalpine Chains, France

Lajos Adam Csicsek[1], Rodney Graham[1], Lidia Lonergan[1], Samuel Brooke-Barnett[1]
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Many of the fold and thrust belts in the Alpine domain (e.g. Betics, Rif, Pyrenees, Carpathians and the Alps) comprise evaporitic successions. The structural style and evolution of these orogens has been affected by salt tectonics. The Southern Subalpine Chains of SE France is one of these mountain belts, and it contains a well-documented succession of Upper Triassic (Keuper) rocks that include gypsiferous evaporite bodies associated with many of the Alpine structures. The Southern Subalpine Chains formed the passive margin of the Alpine Tethys during its Jurassic-Cretaceous rifting and thermal subsidence phase. During the subsequent Alpine shortening the incompetent evaporites and variegated gypsiferous shales have had a significant impact on the development of the fold and thrust belt but the role of the salt-related structures in the preceding passive margin phase is also important.

Detailed geological mapping and section construction was carried out in the vicinity of Castellane, Blieux and Senez. Isolated diapirs including the Chasteuil, Castellane, Boades and Gévaudan diapirs are connected by buried salt-walls. Along the walls and diapirs Triassic evaporites were extruded and welds were formed during the passive margin and the subsequent Alpine evolution. Diapirs, walls and welds are bounded by kilometre scale minibasins containing Triassic to Tertiary aged rocks (e.g. Taulanne basin, Senez basin, Blieux basin, Porte de St-Jean basin, Taloire basin (Figure 1).

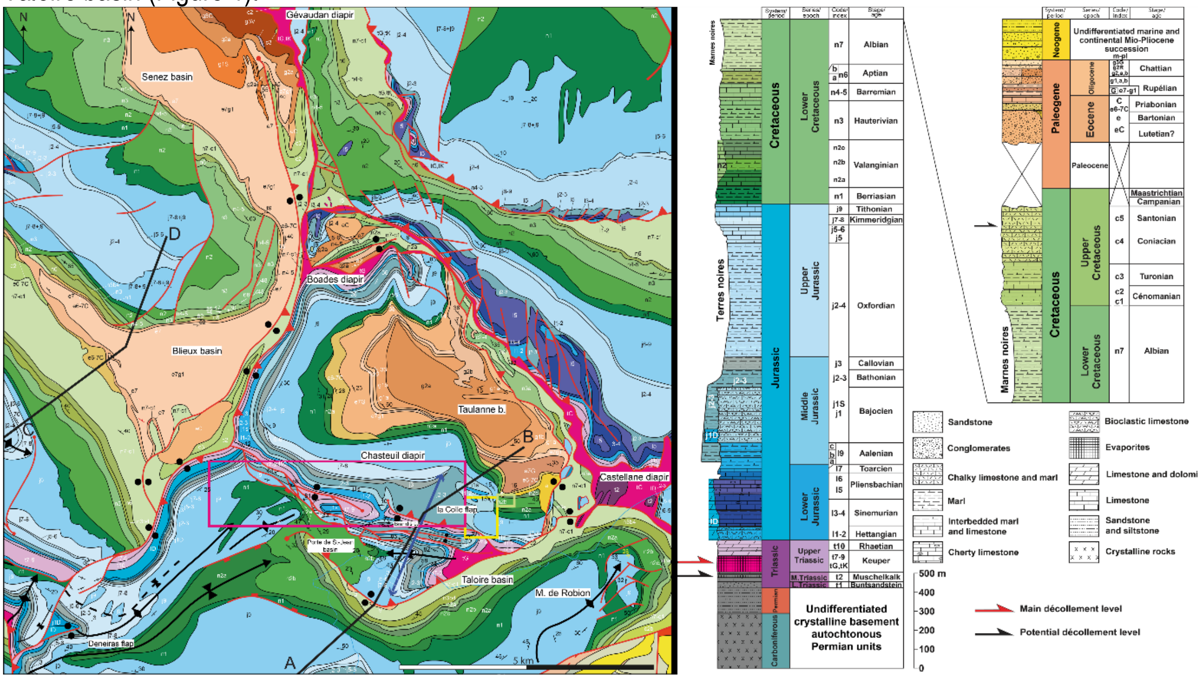

Figure 1 Geological map and stratigraphic scheme of the study area.

Incomplete, condensed and overturned Jurassic-Cretaceous sections (e.g. la Colle flap) adjacent to the Chasteuil diapir represent the elevated roof of the rising diapir. Dramatic thickness changes, stratal and structural geometries suggest that salt structure grew from Figure 1 Geological map and stratigraphic scheme of the study area. Early Jurassic (Hettangian) to Early Cretaceous (Valanginian) times. The structure has subsequently been tightened and further deformed by Alpine shortening from Late Cretaceous to recent times.

In other cases, salt reached the seafloor in an open-toed geometry. Jurassic limestone blocks are “floating” as dismembered roof fragments of the salt structures in Aptian-Albian black shales or in Keuper evaporitic bodies around the Castellane and Boades diapirs which suggests mid-Creatceous extrusion.

The pre-erosional lateral extent of these allochtonous sheets is unclear. However, 1.5 km northeast of the Boades diapir Valanginian rocks are “overlain” by a transported carapace block of Liassic (Hettangian) cherty limestone which may suggest that the allochtonous salt extended a considerable distance. These mid-Cretaceous allochtonous salt sheets around feeder diapirs and along feeder walls also affected the accumulation of Aptian-Albian black shales and Upper Cretaceous sediments. Thickness changes of these deposits within synclines bounded by Triassic gypsum or the equivalent welds (Figure 1) and pinch-outs against these walls and welds suggest that they were deposited in a secondary minibasin on top of the allochtonous salt sheets. These sheets were shortened, squeezed and welded during the subsequent Alpine contractional phase. The syn-orogenic deposition of Tertiary foreland basin deposits was also influenced by the presence allochtonous evaporite sheets. Pre-Eocene conglomerates comprise underlying Cretaceous carbonates deposited locally in the synclines forming preexisting topography from mid-Cretaceous times. Rapid thickness and facies changes are also characterestic in the Eocene-Oligocene succession.

Salt tectonics identified through accurate mapping and cross-section construction shows that there was a significant pre-Alpine salt related deformation throughout Jurassic — Cretaceous times on the European Tethyan passive margin. The structural evolution of the passive margin was effected by salt-tectonics during the syn-rift and post-rift stages of Alpine Tethys. Subsequent Alpine shortening has affected an already deformed succession and modified the older halokinetic structures. The original geometry of salt related structures have had effects on the structural style of the evolving thrust faults and deposition of froeland basin succession.

NOTES:

KEYNOTE: Salt tectonics in the Iberian Atlantic margins: lessons from the Lusitanian Basin and the Southern Pyrenees.

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[2]*Universitat de Barcelona;* [3]*Instituto Geológico y Minero de España*

Many salt-detached fold-and-thrust belts are pierced by salt diapirs. In the earlier literature, these salt structures were frequently interpreted to have originated from thrust tectonics or strike-slip deformation. However, this scenario is largely incompatible with modern perspectives on the deformational processes associated with salt tectonics. It is increasingly well understood that the initiation of diapirs during contraction would only be possible if there was a thin overburden and detachment folds became faulted and eroded. More typically, contraction reactivates and squeezes diapirs that were active prior to shortening. The reactivation of pre-existing diapirs during contraction can lead to the development of distinctive structures by salt expulsion mechanisms. These include allochthonous salt sheets, salt welds and folds with large overturned flaps, all of which overprint and sometimes destroy the original salt tectonic framework. These complications have led to significant confusion in the literature, as is shown by an increasing number of publications reassessing the structural evolution of salt-influenced fold-and-thrust belts (e.g. in the Pyrenees, Alps, High Atlas, Zagros, Flinders Range, etc.). In this talk, two case studies of reactivated Mesozoic diapirs exposed along the Iberian Atlantic margins are presented. These case studies provide key constraints applicable to other salt-influenced fold-and-thrust belts.

In the first example, a new model for the salt tectonic evolution of the Lusitanian Basin at the western Iberian Atlantic margin is presented. The Lusitanian Basin developed during several phases of Triassic and Jurassic rifting associated to the opening of the Atlantic. The first Triassic extensional phase culminated in the deposition of a thick layer of Rhaetian to Hettangian salt. Above this layer, the Jurassic and Cretaceous overburden became largely decoupled from the pre-salt basement and was influenced by the rising of salt structures, which nowadays form wide diapirs piercing thick Jurassic and Cretaceous sedimentary successions. In previous works, these salt structures were interpreted as Jurassic salt pillows, and piercing was thought to occur during Cenozoic shortening. However, the identification of distinct Jurassic halokinetic sequences on exposed diapir flanks indicates a protracted phase of previously unidentified passive diapirism.

Salt movement in the Lusitanian Basin is therefore interpreted to have initiated shortly after the deposition of an Early Jurassic overburden. Two types of salt structures are identified. In areas where the structural trend was orthogonal to the direction of extension, passive diapirs initiated by thin-skinned extension above active, basement-involved, extensional faults, and persisted for the rest of the Jurassic. In areas where the structural trend was sub-parallel to the direction of extension, salt did not pierce the overburden and instead salt anticlines developed. Subsequent Alpine contractional deformation shortened both the diapirs and the salt anticlines. Most diapirs were squeezed and became narrower, but the associated halokinetic strata remained largely unaffected by contractional deformation. In some cases, however, the diapirs were weld shut and the salt walls formed near-vertical thrust-welds, which now connect the remaining diapirs. In contrast, reactivation of the salt anticlines generated new faults sub-parallel to their axes, and further folding. Several of the anticlines were eroded, forming new diapirs. In conclusion, our model suggests that passive salt diapirs in the Lusitanian Basin existed since the Early Jurassic, and thus during almost the entire evolution of the basin.

In the second example, we re-examine the salt tectonic evolution of the Cotiella Basin, located in the southern Pyrenees of Spain. The structure of the Cotiella Basin is dominated by a late Santonian to Eocene thrust system, which transported and uplifted Late Cretaceous extensional faults, detached above relict Late Triassic salt. These faults were interpreted as salt-floored gravity-driven structures developed at the North Iberian continental margin. Subsequent Pyrenean contractional deformation preserved the main extensional features, but most of the Late Triassic salt was expulsed and then dissolved, hardly leaving any indication of the original salt volume.

Based on field research, we demonstrate that the rising of passive diapirs was coeval with gravity-driven extension throughout the entire development of the Cotiella Basin. The rising of salt diapirs controlled the geometry of overlying strata, sediment accumulation and facies distribution. Late shortening squeezed the diapirs, most of them were weld shut and their earlier geological history was masked. Salt evacuation during tectonic inversion explains the presence of folds with large overturned limbs in the area, the kinematic evolution of which would otherwise remain enigmatic.

In conclusion, the application of latest concepts of salt tectonics is essential for studies aimed at unravelling the structural evolution of salt-influenced fold-and-thrust belts. This has direct implications for hydrocarbon exploration, since the timing and nature of diapirism impacts on the distribution of source rocks, reservoirs, seals, structural traps and fluid migration pathways, as well as on the thermal maturity of surrounding rocks.

NOTES:

Regional salt tectonics in the Balearic and Provencal-Liguro deepwater basins of the Western Mediterranean Messinian salt Basin

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[1]*Royal Holloway Earth Sciences Department*

This study investigates gravity-driven, thin-skinned salt kinematic processes in the Messinian salt basins of the Western Mediterranean with particular focus on the evolution of the contractional province in the distal deepwater Liguro-Provencal Basin overlying oceanic crust (Fig. 1).

The Western Mediterranean rifted continental margin formed as consequence of back-arc extension and rotation of the Balearic block along the Spanish continental margin segment and subduction roll back and back-arc extension along the French continental margin segment, due to rotation of the Corsica-Sardinia block which led to the emplacement of oceanic crust in the Miocene. The Cenozoic Mediterranean basins are characterised by geodynamic and tectono-stratigraphic evolution and their post-Messinian gravity-driven salt tectonic processes that can be considered as analogue to early stage salt tectonic processes in older (e.g. Mesozoic) passive margin salt basins which are now either deeply buried or strongly overprinted by the younger post-rift tectono-stratigraphic processes. Hence, in the Mediterranean Cenozoic salt basins we have the opportunity to analyse early stage and active salt tectonic processes in great detail.

This study utilises a wide coverage dataset of 2D Kirchhoff pre-stack time-migrated regional seismic sections provided by Spectrum Geophysical. Regional 2D seismic sections spanning from the Gulf of Lion, Valencia Trough and Balearic Promontory to the Liguro-Provencal deepwater basin are interpreted to document the lateral variation in salt structural styles and distribution of the salt-kinematic domains.

The present-day salt structural architecture results from regional gravity-driven thin-skinned basinward salt tectonic transport since early Pliocene times (c.5 Ma) which results in a characteristic kinematic segmentation of salt tectonic structures with a landward extensional, transitional, and basinward contractional domain (Fig. 2). Salt tectonic styles along Gulf of Lion-Provencal and Balearic – Provencal basin segments (Fig. 2) differ in lateral extents of salt structural domains, amount of shortening in overburden and pre-salt sedimentary and structural configurations. However, characteristic extensional salt structures are comparable on the continental slope in both basin segments consisting of salt-detached listric normal faults and reactive triangular diapirs with variable spacing. In the Gulf of Lions-Provencal basin undeformed tabular salt stretches about 60 km from the base of slope into the basinal plain while in the Balearic-Provencal basin it extends 20 km from the basin slope (Fig. 2).

The contractional salt structures in the deepwater salt basin show variable amounts of shortening and timing and range from low-amplitude salt pillows and poly-harmonic salt-cored folds via medium-high amplitude salt-cored folds to tall passive and contractional diapirs. The landward migration of the contractional domain over time is documented by the late (upper Pliocene-Pleistocene) stage contractional deformation of the basinward part of the former transitional domain. The widths of the kinematic provinces and their evolution over time are partly influenced by changes in the basin geometry and the post-Messinian sediment input. For example, the changes in the geometry of the wide and gently dipping continental slope in the Gulf of Lion margin versus the narrow and more steeply dipping slopes in the Balearic margin are reflected in the variable widths of the kinematic domains of the gravity-driven detached salt system.

We further study the halokinetic processes in the contractional diapiric domain. Preserved sedimentary patterns within minibasin depocenters in the deepwater basin will enable the interpretations of kinematic phases and stages of salt growth and provide insights into the temporal local halokinetic processes and controls.

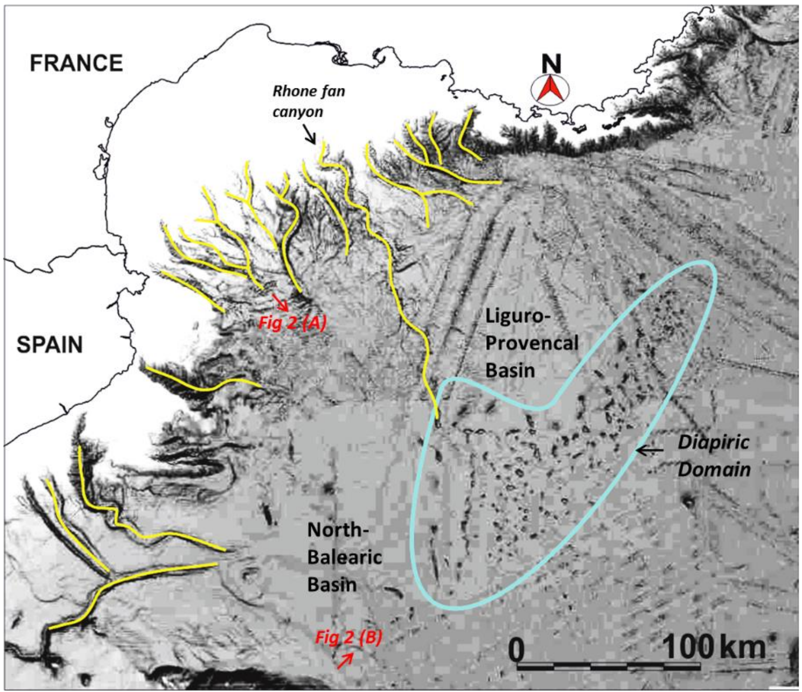

Figure 9: Bathymetric map of the Western Mediterranean reproduced from the GEBCO showing sedimentary pathways and diapiric domain.

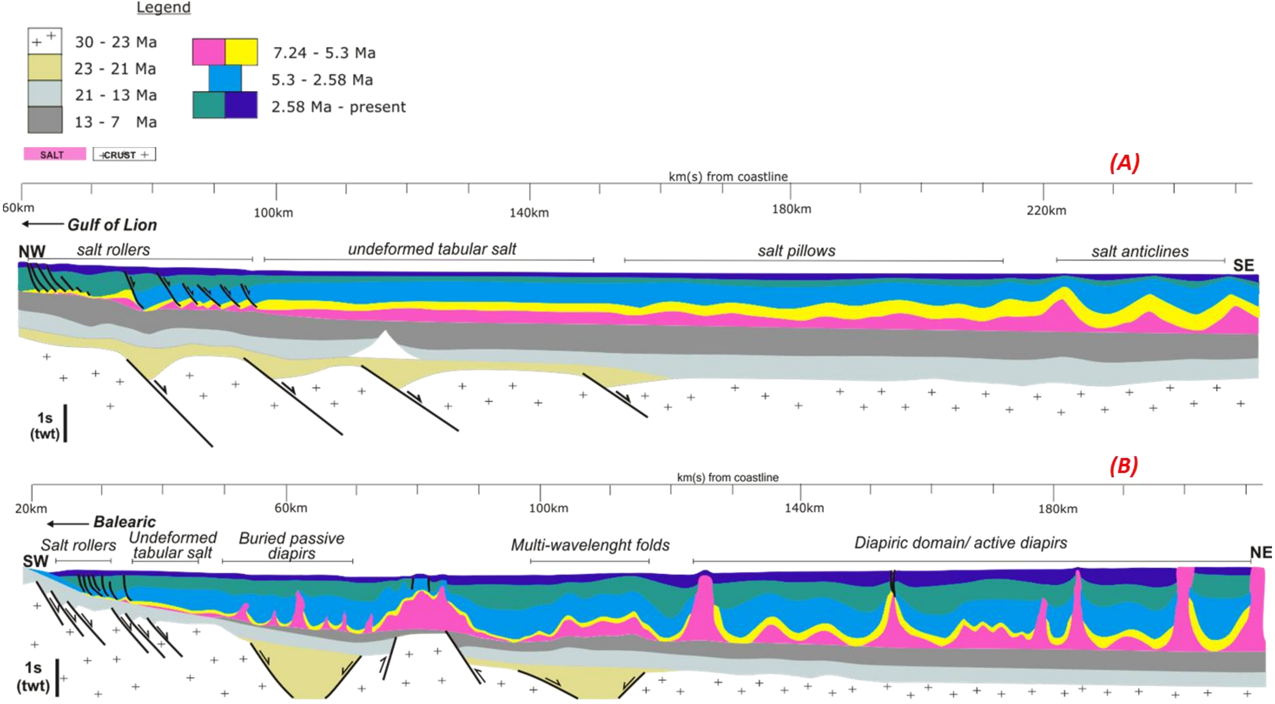

Figure 10: Interpreted 2D seismic dip sections illustrating the regional salt tectonic styles and acoustic basement configuration along (A) Gulf of Lion-Provencal and (B) Balearic-Provencal basin segments.

NOTES:

Intrasalt Structure and Strain Partitioning In Layered Evaporites: Insights From The Messinian Salt In The Eastern Mediterranean

S. L. Evans[1], C. A.-L. Jackson[1]
[1]*Department of Earth science and Engineering, Imperial College London, U.K.*

The Messinian Salinity Crisis is a remarkable geological event which resulted in the widespread deposition of a thick, layered evaporite unit across the Mediterranean Basin, subsequently buried by a thick clastic overburden. The Messinian evaporitic sequence is lithologically heterogeneous. The halite-dominated units are interbedded with other salts, in addition to clastics or carbonates. This lithological heterogeneity can lead to rheological heterogeneity, with the different mechanical properties of the various rock types controlling strain partitioning within deforming evaporites.

Determining the composition and internal structure of salt bodies is important for safe drilling through thick salt sequences, and enables us to build better velocity models that allow more accurate seismic imaging of subsalt geology. However, due to typically poor seismic imaging, and a lack of outcrop and well data, the nature of this lithological control on intrasalt deformation is still poorly understood.

The heterogeneous Messinian evaporites are highly reflective, shallowly buried and only weakly deformed along the Levant Margin in the eastern Mediterranean. This means that they are well imaged by seismic data (Fig. 1) and provides us with a unique opportunity to assess how: (i) intrasalt strain varies within thick salt during the early phase of margin development; and (ii) in the context of the Eastern Mediterranean, how the intrasalt seismic-stratigraphic architecture links to the geodynamic context and evolution of this tectonically complex region.

We use high-quality 2D and 3D seismic reflection data covering a large area offshore Lebanon to map intrasalt structural style. The strong, competent layers embedded within the ductile halite units are highly reflective and deform in a brittle manner, recording intrasalt strain. This enables us to calculate strain on individual intrasalt reflectors to show horizontal and vertical variations across the study area. From this we can determine how lithological and thus mechanical heterogeneity affects the structural evolution of the salt during early stage salt tectonics.

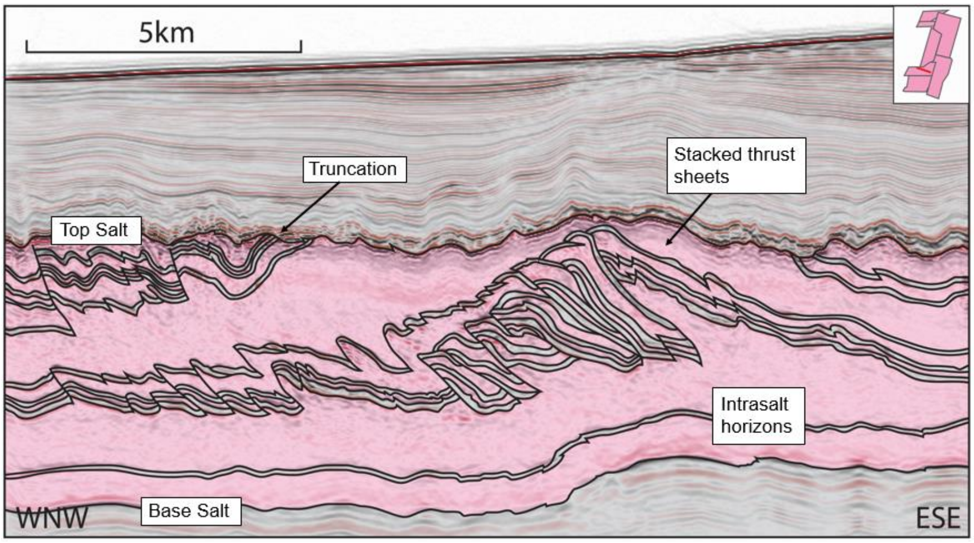

Figure 1 *Location of 3D seismic data and regional context showing distribution of key tectonic elements (modified from Allen et al. 2016).*

NOTES:

Salt Tectonics characterization of the Offshore Tarfaya Basin, NW Africa

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The structure of the Northwest African passive margin between southern Morocco and Canary Islands is in part controlled by the presence of a late syn-rift salt. The topographic relief developed during Triassic rifting (horsts and grabens) constrained the irregular thickness distribution of this evaporitic unit in the Tarfaya Basin (Fig. 1a). The continental siliciclastic and evaporitic (halite) syn-rift unit overlaid the Hercynian basement with a general NE-SW structural trend (Le Roy et al., 1997). The onset of drifting between Toarcian and Bajocian times drove incipient sea-floor spreading (Sahabi et al., 2004). Later, during the Early Cretaceous, a basinwide regression exposed and eroded the Jurassic carbonate shelf. The supplied sediments bypassed the shelf and formed the Tan Tan delta complex, active until Albian times (Wenke, 2014). From Late Cretaceous to Neogene times, compression related to the Eurasian and African plates convergence took place. Prominent uncomformities record these events in the offshore Tarfaya Basin. The easternmost Canary Islands formed by Lanzarote and Fuerteventura have been active at least since Middle Oligocene times (Casillas et al., 2008; Troll & Carracedo, 2016). The formation of these islands significantly modified the Tarfaya Basin geometry compared to the adjacent Agadir and Laâyoune basins (Gouiza, 2011; Wenke, 2014) (Figure 1a).

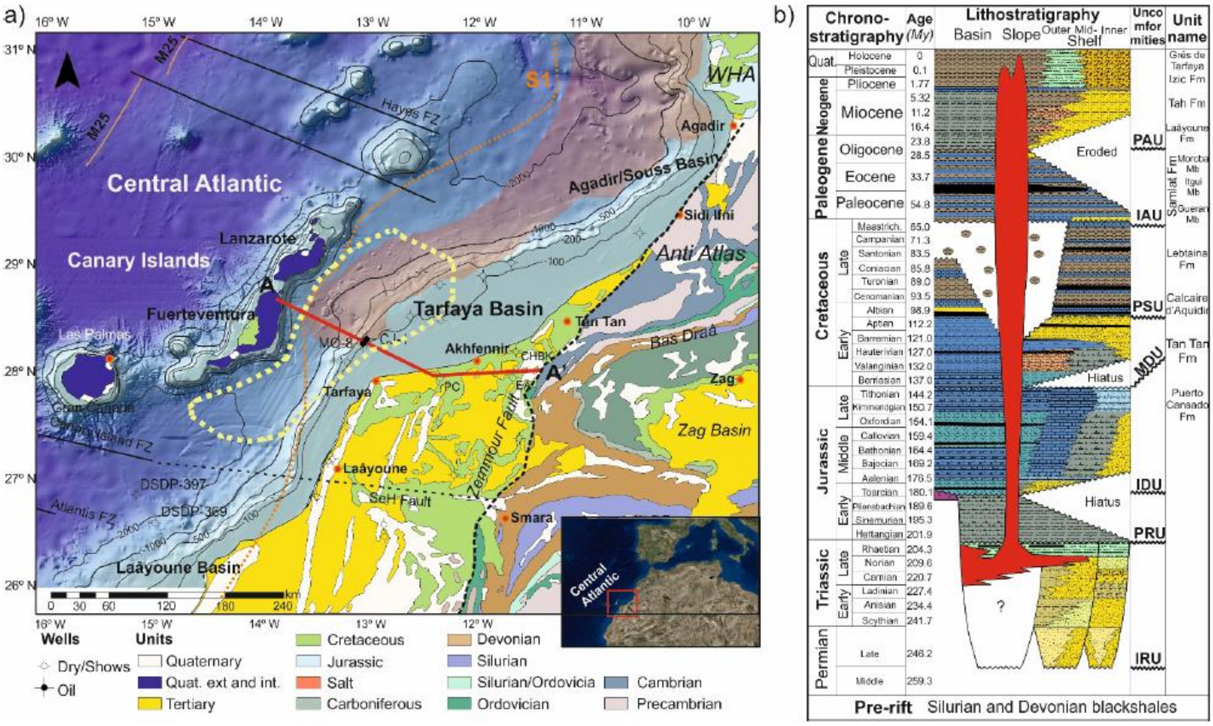

Figure 1 a) Geological map of Northwest African margin, and location of the study area (yellow dashed line). Salt basin is depicted in red. WHA: Western High Atlas. S1 magnetic anomaly constitutes the Ocean/Continent Boundary. b) Stratigraphic chart with the main units and uncomformities. IRU: Initial Rift Uncomformity; PRU: Peak Rift Uncomformity; IDU: Initial Drift Uncomformity; MDU: Mature Drift Uncomformity; PSU: Peak Spreading Uncomformity; IAU: initial Atlasian Uncomformity; PAU: Peak Atlasian Uncomformity (modified from Wenke, 2014).

Through the interpretation of a large 2D/3D seismic dataset covering an area of approximately 30000 km2 between offshore Morocco and Canary Islands (Figure 1a), this study provides for the first time an interpretation of the main salt structures in the offshore Tarfaya Basin. The main structural elements and their variation along strike are presented through the confection of regional cross-sections. Seismic attributes were used to optimize the quality and continuity of reflectors along the basin and allowed to reduce the seismic uncertainty of top and base salt.

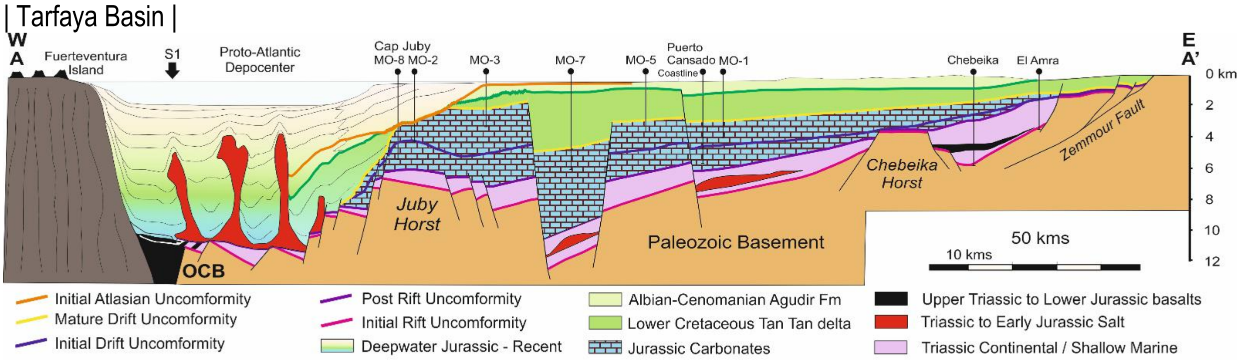

Figure 2 General transect of the Tarfaya Basin including the main elements described in the text. For location see Figure 1a (modified from Davison, 2005).

The interpreted subsalt syn-rift structure of the offshore Tarfaya Basin consists on NNE- to NE-trending half-grabens and grabens, almost parallel to the African coast. These topographic lows are bounded by WNW to NW dipping extensional faults and opposite dipping counter-regional faults. Counter-regional faults also bound different horst structures that divide the Tarfaya Basin into separate depocenters (Figure 2). The sedimentary infill of the basin as well as the original salt distribution and thickness have a clear structural control related to these horsts and grabens. The Proto-Atlantic depocenter (Figure 2) constitutes the deepest sub-basin (12 km thick) where salt was initially deposited. From proximal to distal positions, the most common types of salt structures identified in this sub-basin are salt pillows, anticlines, and diapirs that locally feed allochthonous salt sheets. This salt sheet acts in turn as a local detachment for detachment folds and thrust welded anticlines. Basinwards, the most common salt structures are salt stocks that occasionally form canopies, frequently with flanking expulsion rollovers and salt anticlines. According to our interpretation, salt flow started soon after deposition, since Pliensbachian strata onlaps the salt unit in many cases. The primary mechanism of salt mobilization in this stage is basement involved extension. Thin skinned extension using salt as a detachment in rotated half-grabens might have been a secondary mechanism. Development of the Tan Tan delta complex is thought to have played a key role in the expulsion of salt from proximal areas during the Lower Cretaceous. The onset of convergence between Eurasia and Africa during Late Cretaceous times reactivated subsalt fault blocks and squeezed diapirs. Many of the more proximal salt stocks show primary welding, whereas basinwards many diapirs are still active and extrude.

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Day Two: Session Three – regional – Americas

KEYNOTE: Extensional versus salt-evacuation origin for the Albian Gap of the Santos Basin, Brazil

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The Albian Gap in the Santos Basin is a segmented, linear system of depositional troughs, some 300 km in length, in which the Albian carbonates are mostly missing (over a width of up to 50 km) and the overlying Upper Cretaceous to Paleogene strata dip and thicken basinward in a complex monoclinal structure above the Aptian salt weld. Two principal interpretations of its origin have been advanced over the past 25 years: 1) it represents an expulsion-rollover structure, in which the shifting vertical subsidence was matched by distal salt inflation but no lateral movement of the overburden; or 2) it represents the hanging wall of a counterregional extensional fault system in which the overburden in the footwall moved basinward during gravitational failure of the margin.

A combination of modern prestack depth-migrated 3-D seismic data and regional relationships is used to argue, based on several lines of reasoning, that only the extensional model is compatible with the observations and that the expulsion-rollover model is inappropriate. First, there are smaller-scale extensional structures such as reactive diapirs and both down-to-the-basin and counterregional faults associated with the larger rollover structure. Second, there is a gradual transition along strike from basinward-dipping faults to conjugate sets to counterregional faults. Third, there is significant age-equivalent shortening in more distal positions, yet the Albian Gap is the only candidate for the matching extension. Fourth, ramp-syncline basins record a minimum of 30 km of basinward translation. Finally, the rollover geometry of the Albian Gap, in which the strata terminate downward sharply onto the salt weld, contrasts with a more proximal rollover where the strata have sigmoidal geometries representing a true expulsion rollover, with the two structures separated by the Merluza fault, a large landward-dipping presalt fault that offsets the salt level by up to 3.5 km.

The Albian Gap overlies the northern extent of a presalt rift basin and is located just landward of the São Paulo Plateau, which was a high before, during, and after salt deposition. Because the salt generally dipped landward in this area, differential loading resulted in gravity spreading accommodated by counterregional extensional faults. In contrast, where the presalt and salt dipped basinward, both to the NE and SW of the north-central Santos Basin, the more typical scenario of basinward-dipping faults was predominant.

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Base-Salt Relief Controls on Salt-Tectonic Structural Style, São Paulo Plateau, Santos Basin, Brazil

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Base-salt relief influences salt flow, producing three-dimensionally complex strains and multiphase deformation within the salt and its overburden. Understanding how base-salt relief influences salt-related deformation is important to correctly interpret salt basin kinematics and distribution of structural domains, which have important implications to understand the development of key petroleum system elements. The São Paulo Plateau, Santos Basin, Brazil is characterized by a >2 km thick, mechanically layered Aptian salt layer deposited above prominent base-salt relief. We use 3D seismic reflection data, and physical and conceptual kinematic models to investigate how gravity-driven translation above thick salt, underlain by complex base-salt relief, generated a complex framework of salt structures and minibasins. We show that ramp-syncline basins developed above and downdip of the main pre-salt highs record c. 30 km of Late Cretaceous-Paleocene basinward translation. As salt and overburden translated downdip, salt flux variations caused by the base-salt relief resulted in non-uniform motion of the cover, and the simultaneous development of extensional and contractional structures. Contraction preferentially occurred where salt flow locally decelerated, above landward-dipping base-salt ramps and downdip of basinward-dipping ramps. Extension occurred at the top of basinward-dipping ramps and base-salt plateaus, where salt flow locally accelerated. Where the base of the salt layer was broadly flat, structures evolved primarily by load-driven passive diapirism. At the edge of or around smaller base-salt highs, salt structures were affected by plan-view rotation, shearing and divergent flow. The magnitude of translation (c. 30 km) and the style of salt-related deformation observed on the São Paulo Plateau afford an improved kinematic model for the enigmatic Albian Gap, suggesting this structure formed by a combination of basinward salt expulsion and regional extension. These observations contribute to the long-lived debate regarding the mechanisms of salt tectonics on the São Paulo Plateau, ultimately improving our general understanding of the effects of base-salt relief on salt tectonics in other basins.

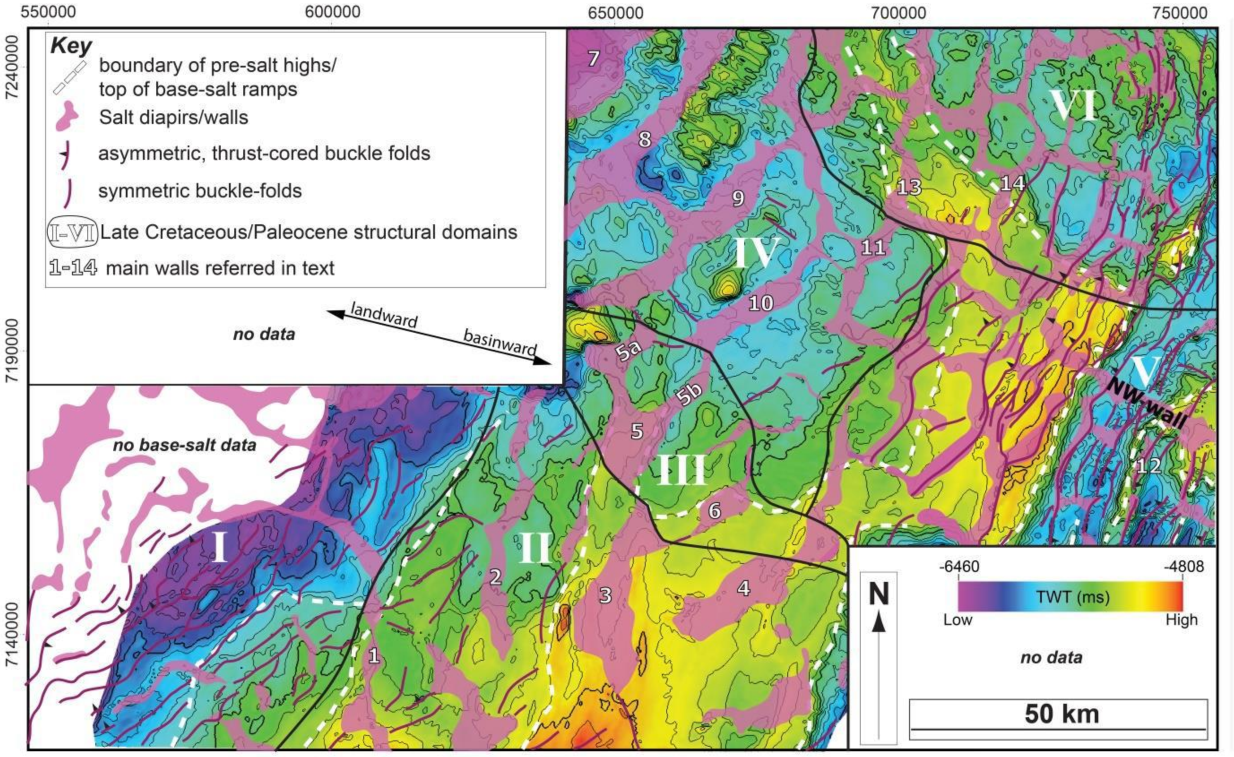


Figure 1: Overlay of salt structures over depth-corrected base-salt map illustrating the distribution of structural domains and their relationship with base-salt topography.

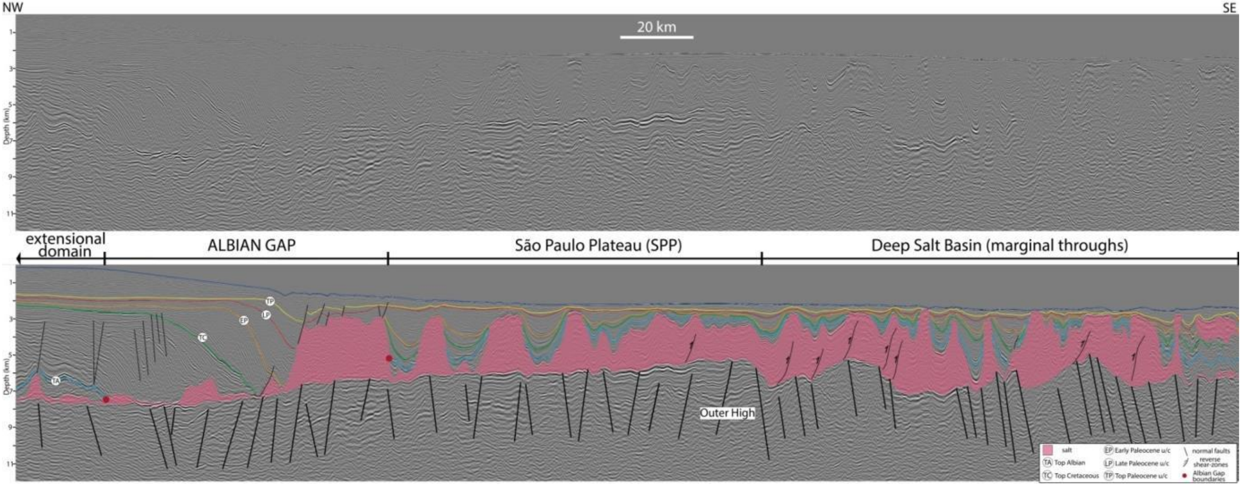
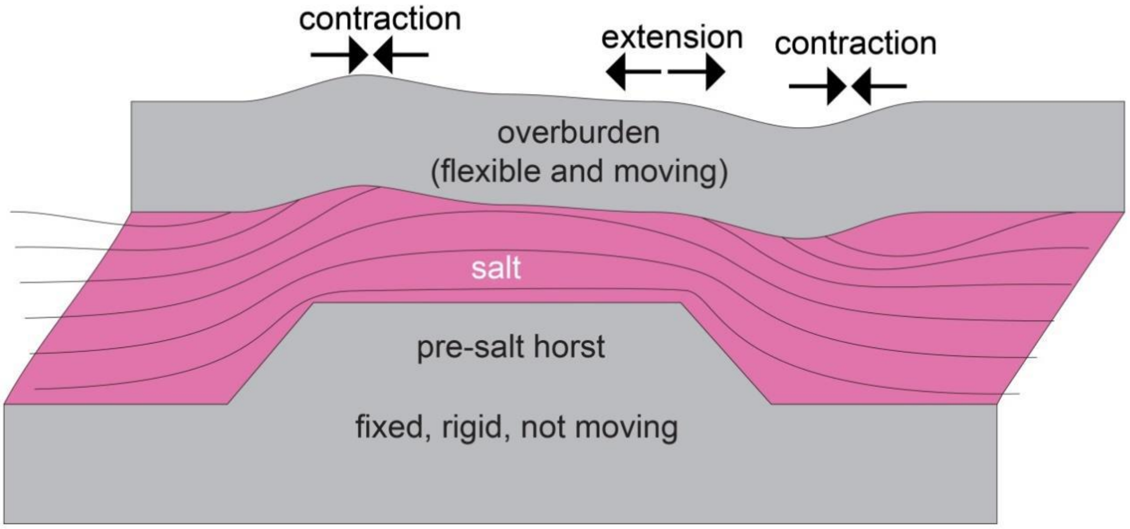


Figure 2: Uninterpreted and interpreted regional PSDM (pre-stack depth-migrated) line showing the main salt-related structural elements of the Central Santos Basin: an updip extensional domain, a c. 60km of Albian Gap, The São Paulo Plateau (SPP) and a deep-salt basin domain characterized by high-amplitude, squeezed diapirs and allochthonous salt sheets. The base-salt geometry is characterized by a series of landward- and basinward-dipping base-salt ramps with up to 2 km of structural relief associated to rift normal faults that generate base-salt drape folds and/or small offsets.

(a) Idealized flow-profile for the SPP



(b) Flow profile with neglible roof

(c) Flow profile with thick roof

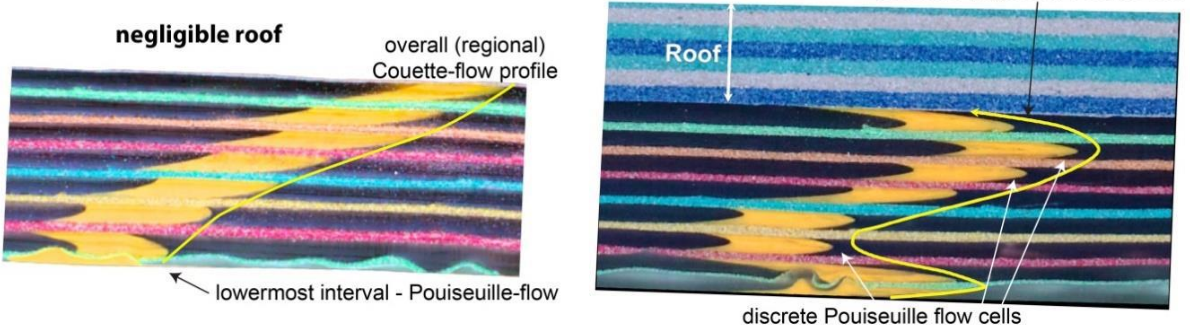


Figure 3: Idealized viscous shear drag (i.e. Couette flow) model showing salt streamlines (black line) and flux variations across base-salt relief that resulted in the observed deformational style in the SPP. Salt inflation and contraction over base-salt landward-dipping ramps (horst updip edge) and subsidence with updip extension and downdip contraction over base-salt basinward-dipping ramps (horst downdip edge). (b)-(c) Physical models simulating salt-detached translation of a mechanically-layered salt with (a) negligible roof and (b) thick roof showing a first-order Couette flow profile and more variable second-order flow; both of which evolve through time and become more complex and affected by Poiseuille flow as the overburden thickens (adapted from Weijermars et al., 2014). Viscous silicone polymer simulating salt (black) alternates with frictional-plastic dry sand (thin, coloured layers, each 1 mm thick). Yellow parabolas represent originally vertical passive markers within the salt.

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Geodynamic modelling of salt movement: a 2D example from Santos Basin, Southeast Brazil

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The salt movement in sedimentary basins is usually approached by a kinematic point of view. Kinematic approaches usually give consistent geometries in an easy way. But salt movement not only affects the sedimentary distribution. In fact, it also affects the stress field and temperature distribution, which are relevant for pore pressure prediction and source rock maturity in sedimentary basins. Looking for these answers, a geodynamic approach is required.

The mechanism of salt movement has been widely debated (Hudec and Jackson, 2007). It is recognized that, although salt bodies are overall less dense than their overburden, the resulting buoyancy forces are not the main drive behind salt flow. Instead, salt flow is assumed to be dominantly driven by differential loading, often divided in three types: gravitational, displacement and thermal. These processes can occur simultaneously, and they are often affected by the stress field, pore pressure and temperature conditions, which are controlled by the geodynamic evolution of the basin. This work adopts numerical modelling to simulate the geodynamic process in order to better understand the geomechanical attributes variations in salt body and adjacent layers. For the geodynamic simulation, considering plane strain conditions, was developed an Arbitrary Lagrangean Eulerian (ALE) code. It was assumed that the salt behaves as an incompressible and viscoplastic material, obeying the Stokes equations. Since temperature evolution affects and changes properties, such as density and viscosity, the temperature field is computed by solving the heat transport. The rheological behavior of the salt is simulated using both diffusion and dislocation creep mechanisms. Thus, a general power law creep is used to describe the effective viscosity of the salt. It was considered, for the sediments around the salt layers, the Mohr-Coulomb constitutive model.

It is used 2D seismic sections from the Santos basin located in the southeast Brazilian margin to construct our numerical examples. The Santos Basin started as an intracontinental rift (~130 Ma), filled by lacustrine sediments, overlain by a salt layer which can reach approximately 3.5 km thick at the age of its deposition at Aptian time (Mohriak et al, 2008). From the Albian deposition of carbonate sediments until the present day marine siliciclastic-bearing deposition, the salt layer has been flowed forming extensional structures often observed in proximal margin and compressional structures observed at more distal margin.

That model has been able to reproduce the evolution of salt structures and the deformed sedimentary layers frequently observed in the Santos Basin, reproducing measured data such as stresses, pore-pressures and temperatures. The proposed geodynamic approach has been proved to be used as a consistent tool for better understanding the salt flow, and its influence in stresses, deformations, pore-pressures, temperatures fields. As a consequence, this workflow provides direct application for well drilling projects.

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Salt Styles and Their Controls in Santos and Campos Basins, Brazil

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The Salt Basins offshore Brazil accumulated kilometers of layered anhydrite, halite and other bittern salts (Layered Evaporite Sequence, LES or “salt”) during the early opening of the South Atlantic in the late Aptian. Unlike the halite dominated salt of Gulf of Mexico, the salt in Brazil displays many modes of internal deformation that can be used to understand salt flow within the basins and variations in deformation of the salt along dip and strike directions. This study considers three aspects of the salt in the Santos and Campos Basins:

1. The composition of the salt and its variation across the basins using seismic attribute techniques to delineate areas of thin salt with a major component of remaining basal anhydrite, areas of salt dominated by LES, and areas of thick halite. There are distinct compositional differences across the basins with some characteristics being unique to either of the basins.

2. The internal salt deformation styles and how it is controlled by the salt lithology and salt budget. Salt architecture and internal deformation can be directly correlated to the internal composition of the salt viz. LES dominated areas displaying multilayered folding and thrust imbricates, whereas areas of thick halite with minor embedded anhydrite display ptygmatic buckle folds; and, the thick halite dominated salt in the outboard part of the Santos basin forms large canopies similar to the Gulf of Mexico.

3. The use of a number of basin-wide balanced cross-sections to understand salt flow patterns and structural evolution of salt basins: Salt is one of the most unconstrained units in structural restorations due to its non-plane strain deformation characteristics, thereby making it difficult to estimate total budget both at initial and incremental stages of restoration. As a possible solution to the problem, the structural restorations utilize locations of internal salt deformation to estimate shortening; and, areas of thin depositional salt such as Cabo Frio and Sugarloaf highs to estimate depositional salt thickness. Several structural restorations across the basins imply that most of the lateral movement was accommodated very early in the history of the post salt basins. Moreover, updip extension in the Santos was not completely translated to downdip contraction at the outermost limit of depositional salt but was taken up by folds and thrusts about halfway across the basin along the Outer Basin High and Sao Paolo Plateau.

All of these aspects provide new insights and challenge our current understanding of salt and its deformation in Brazil.

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Tectono-sedimentary framework of a Permian salt formation in the northern Peruvian fold-and-thrust belt

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In the northern Peruvian fold-and-thrust belt (NPFTB), it has been recognized salt diapirs and hydrocarbon accumulations. A key element to understand the formation of these structures and the petroleum system is to establish the tectono-sedimentary evolution from presalt to suprasalt lithostratigraphic units deposited during the Permian and Triassic ages, respectively. It has been suggested that these units contain potential reservoirs and source rocks. In addition, a proven carbonate reservoir, with an estimated Permian age, has been discovered in the subsurface (Shanusi well). On salt unit, it is poorly known the tectonic regimen that controlled their deposition, the sedimentary model and the sub-sequent deformation. On the basis of detailed field observations in salt/sulphate diapirs, well-logs and 2D seismic images, the main aim of this presentation is to show the tectono-sedimentary features of the evaporites.

We show siliciclastic (shale and sandstones) layers prevailing in the most external areas of an evaporite basin. These layers are forming part of a thin (100 m thick) succession deposited on a detrital mudflat. To the inner parts, anhydrite/gypsum wedges are observed with intercalated thin (up to 30 m thick) carbonate and siliciclastic intervals. Carbonates contain dolostone and shale, characterized by local porosity and significant TOC (4%), respectively. The sulphate wedges are constituting by thick (up to 600 m thick) successions sedimented on a platform. In the central basin, halite abounds forming a thick body of up to 1200 m thick. The evaporites were sealed by a regional carbonate succession of up to 100 m thick. Structural features and stratigraphic relations give us evidences that the evaporites sedimented in a compressional setting.

The results of our work revels that the evaporites of the NPFTB were deposited in a basinwide characterized by a sulphate platform and a salt basin. This basinwide was generated in a foreland basin related to the Gondwanide Orogeny. The platform is formed of petroleum features, such as reservoirs (in dolostones) and source rocks (in shales). Analogue producer reservoirs and source rocks have recently been described in evaporites of the Zechstein basin (north Europe). Also, in the NPFTB, it is interpreted that compressional fracturation on the presalt unit prevailed, at least, until the salt deposition increasing the potential, as reservoir, of this unit. We expect this presentation is relevant to better understand the relationships between tectono-sedimentary features of an evaporite formation affected by salt tectonics and petroleum accumulations.

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Passive and reactive diapir growth and carbonate sedimentation in the Sureste Basin, SE Mexico and the Basque-Cantabrian Basin, NE Spain

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Two contrasting modes of sedimentation associated with the syn-depositional growth of salt diapirs have been recognised in the Sureste Basin in Mexico. Diapirs that develop in relatively shallow water settings become sites of carbonate platform growth that forms a roof to the diapir restricting further diapiric growth. Re-activation of these salt diapirs by pre- or early Laramide tectonism, in the Sureste Basin, resulted in the development of widespread carbonate breccia systems. In contrast, diapirs that develop in settings unfavourable for carbonate production do not develop a roof and develop as passive structures. The salt may emerge on the former sea floor with the deposition and reworking of insoluble components. Facies associated with passive diapirs have minimal reservoir quality.

Cretaceous carbonate breccias form important reservoirs in the offshore of the Sureste Basin in SE Mexico. Although these breccias are mainly late Cretaceous in age, they pre-date the K/T boundary deposit and they also occur more rarely in the early Cretaceous. They comprise thick deposits of very coarse cobble to boulder-sized clasts that were derived from shallow water platform interior settings and deposited by various mechanisms including debris flows, grain flows and turbidites. Breccias are interbedded with pelagic carbonates implying separate multiple depositional events that took place in a basinal setting. The extreme coarse grained nature of the sediment implies very proximal deposition close to a carbonate platform. Some breccia bodies include clasts with karstic fabrics and intervals of collapse breccia suggesting that some wells may have penetrated *in situ* karsted carbonate platforms. These carbonate breccias are remote from possible detrital sources such as carbonate platforms located over the Yucatan and Chiapas basement blocks. The breccias are interpreted as the reworking of transient carbonate platforms nucleated over reactive salt diapirs. In the Sureste Basin, tectonic events have been recorded of mid- to late Cretaceous age that may represent early or pre-Laramide events. This would provide the stimulus for the reactive growth of salt diapirs and associated carbonate platform development. These flank deposits are steeply-dipping and may be further rotated during later diapir growth; if encountered in vertical wells this may give the impression of a thick breccia deposit. This model of the interaction between syn-depositional salt movement and carbonate production allows proximal carbonate breccia reservoirs to be generated in basinal areas.

A comparison can be made with the Bakio salt diapir and associated Albian carbonate breccias in the Basque-Cantabrian Basin in NE Spain. Here, diapir growth of Triassic salt, including embedded Triassic mafic rocks occurred during the main extensional events recorded in the Basque-Cantabrian Basin. This caused the development of sea floor topography over which a carbonate platform was initiated during the early Albian. This caused the development of sea floor topography on which a carbonate platform was initiated during the early Albian. The aggradation of the carbonate platform created steep margins and caused shedding of carbonate breccias down the flanks of the diapir. Some clasts within the carbonate breccias contain evidence of karstification suggesting that the carbonate platform had been exposed either by sea level drop or further growth of the diapir. The diapir flank deposits comprise steeply-dipping packages separated by angular unconformities that were rotated by drape over a growing structure rather than by post-depositional drag. This indicates several episodes of diapiric growth accompanied by carbonate platform development and shedding of carbonate breccias. However, the presence of a thick diapir roof formed by the carbonate platform loaded the salt and possibly restricted further passive growth of the Bakio diapir. Therefore, further growth was achieved by destruction of the carbonate roof by faulting linked to the regional extensional events occurring during the Albian in the Basque-Cantabrian Basin.

A further unusual breccia-type has been recognised in the Sureste Basin, Mexico, that may be associated with the development of passive salt diapirs. This consists of sorted and stratified breccio-conglomerate with clasts of Tithonian black shale, Kimmeridgian dolomite and pelagic mudstone in a carbonate mudstone matrix that contains middle to late Cretaceous planktonic foraminifera. No shallow platformal clasts are present. Image logs show that the breccia is stratified with graded bedding and evidence of scouring between beds. This is interpreted as a deposit formed by the emergence of salt on the former sea floor with the reworking of insoluble clasts above a passive salt diapir. In this case, the diapir may have developed in a setting that was unfavourable for carbonate production over its crest. In such cases, no diapir roof formed so that diapir growth was unconstrained and the salt was able to reach the sea floor, where it was dissolved and the insoluble residue reworked. This may represent a depositional setting analogous to the brine-pools and brine rivers that occur on the present day floor of the Gulf of Mexico.

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Salt Tectonics in the Eagle Basin, Colorado: A New Example of Thick-Skinned Shortening of Salt Walls and Minibasins

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Combined field mapping, measured stratigraphic sections, and balanced cross-sections of the Pennsylvanian-aged Eagle Valley Evaporite and overlying Late Pennsylvanian to Jurassic-aged strata indicate a long-lived phase of salt tectonics in the Eagle Basin, central Colorado. Diapiric salt structures exposed at the surface represent a series of formerly connected, polygonal salt walls flanked by deep, elongate minibasins in the southern part of the basin. Previous work in this area interpreted these structures to be the result of the Laramide Orogeny and younger tectonism; however, the proposed phase of salt-influenced deformation in the Eagle Basin has a similar history to the Paradox Basin to the southwest and suggests a new paradigm for the tectonic and stratigraphic evolution of this region.

The late Paleozoic Eagle Basin formed as a flexural foreland basin, primarily in Pennsylvanian to Permian time, associated with the neighboring uplifts of the Ancestral Rocky Mountains, i.e. the Front Range, Sawatch, and Uncompahgre highlands. Cyclic flooding and desiccation of the Eagle Basin during Atokan-Desmoinesian time due to glacioeustatic sea-level cycles led to the deposition of a thick sequence of evaporates containing cyclic deposits of halite, other salts, carbonates, and clastics of the Eagle Valley Evaporites, markedly similar to those of the coevally deposited Paradox Formation in the Paradox Basin to the southwest. Structural and stratigraphic analysis of four key regions of the Eagle Basin offers compelling evidence for long-term deformation compatible with salt tectonics prior to the Laramide Orogeny. The following features support the interpretation of a prolonged salt tectonic history subsequently overprinted by tectonic shortening: (i) over-thickened, unconformity-bound strata contain abundant growth structures and represent Permo-Triassic minibasins, which subsided into mobilized Eagle Valley Evaporites; (ii) north-northwest trending linear structures cored by evaporites represent former diapiric salt walls that grew during Pennsylvanian through Triassic time between minibasins; and (iii) Laramide-age shortening resulted in basinal contraction and welded salt walls that were reactivated as thrust structures.

Significant variations in the thickness of the Maroon, State Bridge, and Chinle Formations across the Eagle Basin are representative of a prograding system of north-northeastward younging minibasins, which formed by the passive downbuilding of the clastic systems into the mobilized Eagle Valley Evaporites. Inter-formational angular unconformities and highangle truncation surfaces in Pennsylvanian- to Triassic-aged units adjacent to interpreted paleo-salt wall locations represent halokinetic folds and potentially composite halokinetic sequences. Additionally, near vertical dipping strata of the Gothic and Maroon Formations with interpreted multi-kilometer vertical relief and folding width mapped along the Castle Creek fault zone are suggestive of megaflap geometries.

This work has significant implications for the timing and magnitude of both Ancestral Rocky Mountain uplifts and Laramide-age shortening. Additionally, diagnostic structural and stratigraphic features present in the Eagle Basin are analogous to salt-dominated regions that have undergone shortening of pre-existing diapirs and minibasins such as the Sivas Basin of Turkey, the Western Gulf of Mexico, and the Pyrenees, Zagros, and Flinders Ranges. This study is also critical to understanding the evolution of salt basins that have been subjected to basement-involved shortening, a previously relatively poorly documented aspect of salt tectonics.

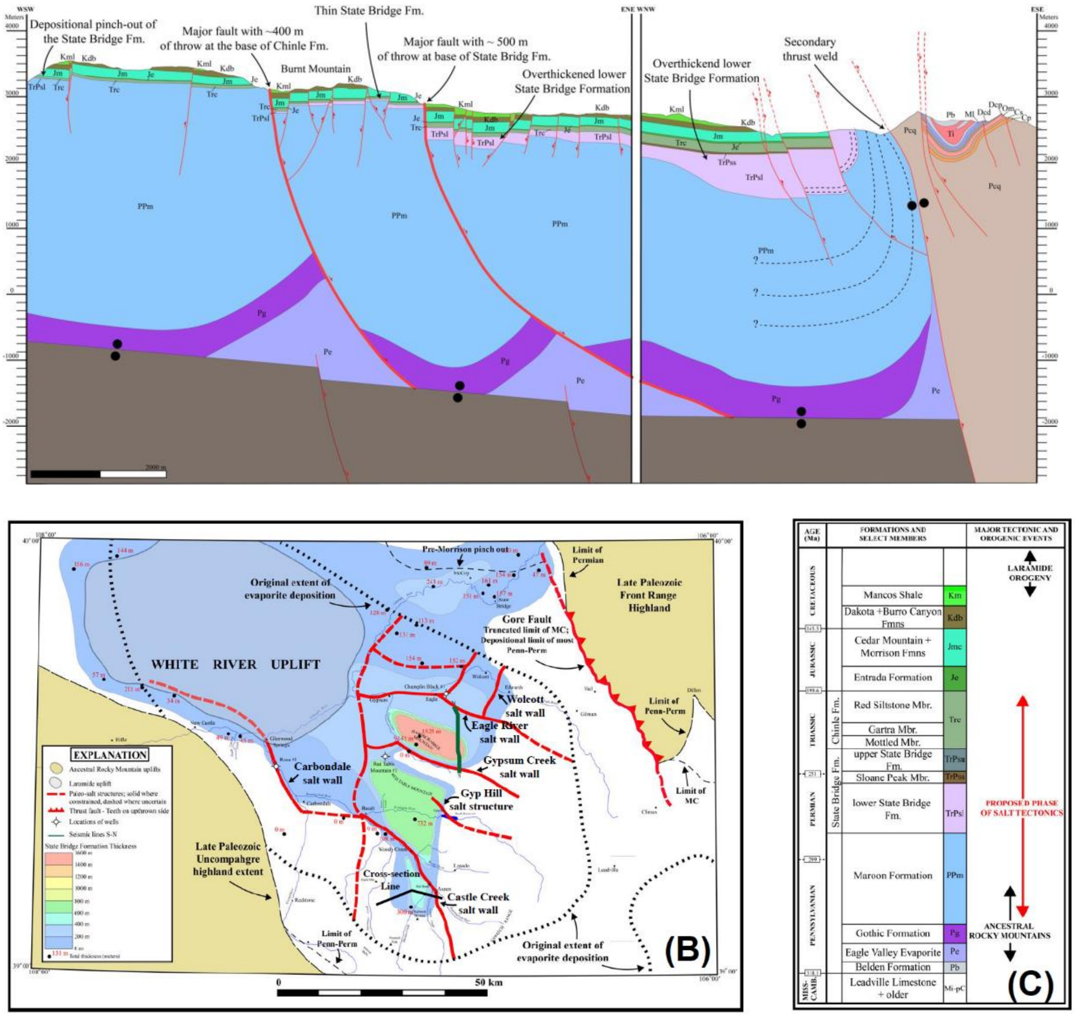

Figure 1. Examples of interpreted salt-related features from the Eagle Basin, Colorado. (A) WSW-ESE, 1:1 composite geologic cross-section illustrating pre-Laramide normal faults, interpreted as large-scale growth faults, detached on autochthonous salt rollers. The over-steepened Maroon Formation observed at the surface beneath a Permo-Triassic unconformity is a potential megaflap extending upward along the flank of the interpreted secondary weld from deep in the subsurface.

(B) Paleo-tectonic features of the Late Paleozoic in west-central Colorado, overlain by a provisional isopach map of the State Bridge Formation (gross thickness) across the Eagle Basin. Note the conceptual locations of a polygonal network of paleo-salt structures (likely salt walls) that dissect the Eagle Basin, based on locations where evaporites are located at the surface and proximal strata indicate halokinetic deformation. The location of the present day White River Uplift has been included as all relevant stratigraphy in that region has been eroded preventing interpretation. The distinct over-thickening of the State Bridge Formation north of Woody Creek in the Aspen region and at Hardscrabble Mountain are interpreted as locations of likely Permo-Triassic minibasins. (C) Summary stratigraphic column for the Eagle Basin with the major Ancestral Rocky Mountain and Laramide orogenies highlighted, along with the interpreted long-lived phase of pre-Laramide salt tectonics.

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Day Three: Session Five - Modelling

Hydrating anhydrite under stress: Implications for the mobility of rock salt in the subsurface

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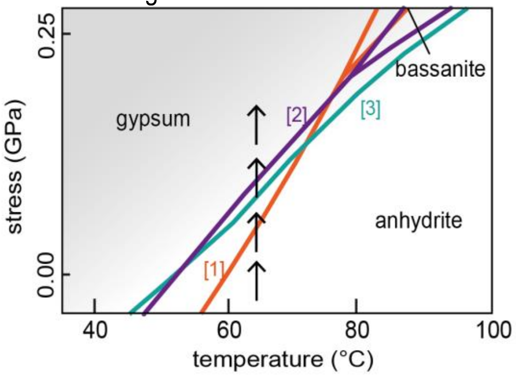
Rock salt deposits predominantly consist of three evaporitic phases: halite, anhydrite and gypsum. The modal composition of rock salt initially depends on the composition of the precipitating source aqueous solution and the natural precipitation sequence of evaporate minerals. But secondary phase transitions via (de)hydration processes is common in nature if water is available (e.g. Farnsworth, 1925; De Paola et al., 2007; Bedford, 2017). Although the phase stabilities in the system CaSO4*H2O are a well-studied field, there is still a degree of uncertainty which is visible in Figure 1.



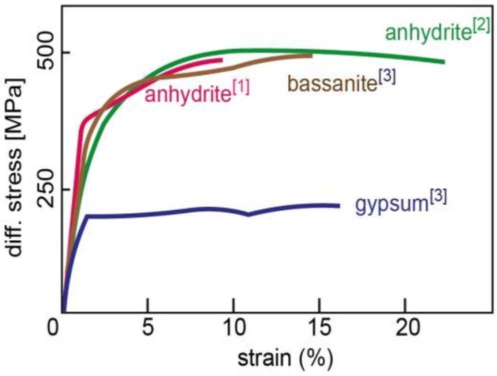


*Figure 1: Section of the phase diagram of the CaSO4*H2O system, arrows show hydration path from anhydrite to gypsum. [1] Klimchouk, 1996; [2] Mirwald, 2008; [3] Bedford, 2017.*

Figure 2: Stress strain curves of compression tests at room temperature, 200 MPa confining pressure and strain rates of 10-3-10-5s-1. [1;2] Handin and Hager, 1957; 1958 (wet); [3] Olgaard et al., 1995.

Previous hydration experiments have focused on the effects of temperature, particle size of anhydrite powders, activators, nucleation and ratio of solid to liquid (e.g. Leininger et al., 1957; Freyer and Voigt, 2003; Sievert et al., 2005). The main reason for the lack of hydration experiments and absence of recorded hydration after dehydration experiments is the necessary timescale (e.g. Conley and Bundy, 1958; De Paola et al., 2009; Bedford, 2017). However, there have been various dehydration and compression tests (Figure 2), as well as hydration experiments with anhydrite powder, brine solutions and elevated temperatures but real rocks are known to experience conditions that fall outside this range, especially with respect to stress conditions.

Combining the well-established phase diagram that describes P and T conditions achievable in the lab with the knowledge about activators enables us to test the effects of stress, strain rate, temperature, fluid pressure and fluid chemistry on hydration reactions under dynamic conditions i.e. under imposed stress. We use natural anhydrite rock samples with different modal gypsum contents for wet triaxial deformation experiments to investigate the hydration of anhydrite to gypsum. Tests have been performed using a range of differential stresses, confining pressures, fluid pressures, fluid chemistry, temperature, elapsed time and strain rates (Figure 3). All samples have been analysed before and after the hydration experiments via optical microscopy, scanning electron microscopy and EBSD.

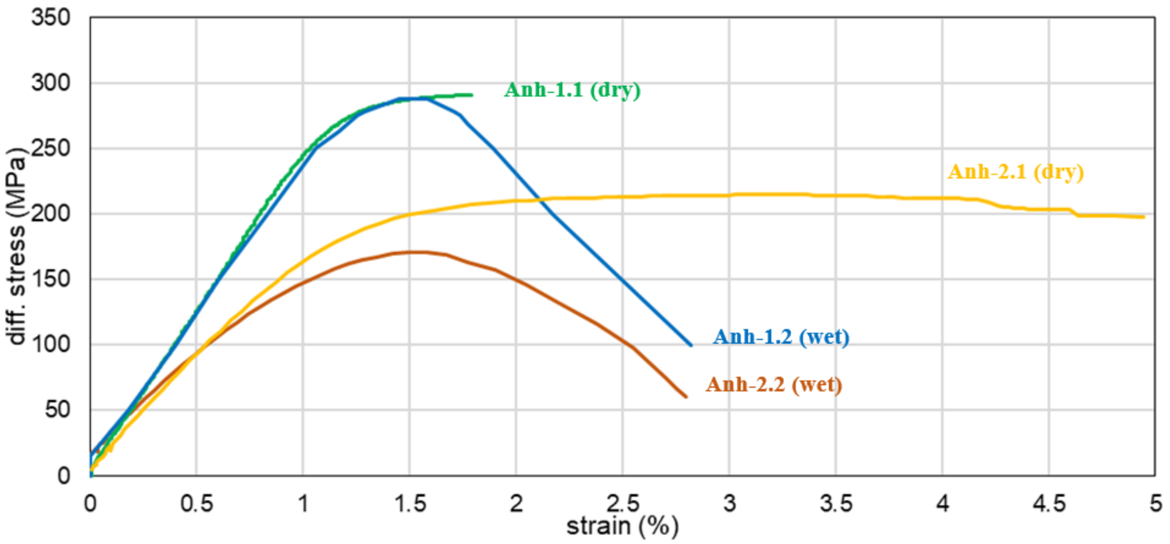


*Figure 3: Stress vs. strain curves anhydrite failure and hydration experiments, all conducted with a triaxial press (TRI-X 250/200) from Sanchez Technologies at 20°C and with a confining pressure of 50 MPa. Anh-1.1 (dry): strain rate = 9.7*10-6s-1; Anh-1.2 (wet): fluid pressure = 40 MPa, strain rate = 9.7*10-6s-1; Anh-2.1 (dry): strain rate = 9.7*10-5s-1; Anh-2.2 (wet): fluid pressure = 40 MPa, strain rate = 9.7*10-5s-1.*

A better understanding of the role of differential stress in either promoting or inhibiting hydration of anhydrite to gypsum will help us to define the conditions under which rock salt bodies can weaken and flow in the subsurface.

NOTES:

Response of a viscous layer of finite thickness to surface loading and its applications to incipient salt tectonics

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Here we discuss quasi-static solutions for the sinking rate of a buoyant body that is placed upon a viscous layer (Figure 1). Problems of this kind are encountered by geologists dealing with the response of a shale or salt substratum to surface loads, when it can be described in an approximate way by a viscous constitutive law. In the following we review existing and also present new analytical solutions for the subsidence into a salt layer of an extended rectangular surface load that will form a local depocentre and thus influence the subsequent structural development. These analytical results can serve well for validating solutions obtained by numerical modelling schemes.

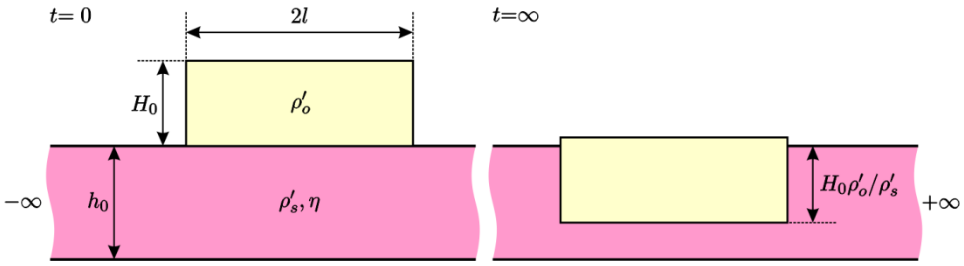

Figure 1. An instantaneously placed buoyant rectangular body of thickness H_0 *and width 2l (yellow) subsides under its own weight into a viscous substratum of uniform height* h_0 *and infinite lateral extent (pink). As time t approaches infinity, the final depth reached by the buoyant body must be consistent with Archimedes' principle, where* ρ'_o *and* ρ'_s *are the effective (buoyant) densities of 'overburden' and 'salt' (with viscosity* η*), respectively.*

We seek solutions for the viscous substratum thickness $h(x,t)$ and consider three possible approaches to this problem: (1) The surface load is rigid and the viscous substratum is squeezed out by pure Poiseuille flow. The stress at the exit points ($|x| = l$, $y = h$) is assumed to be hydrostatic. (2) The surface load is a dead load (heterogeneous vertical simple shear that neglects the load's shear resistance) and the squeeze flow is determined by lubrication theory assuming zero horizontal movement at both the substratum's surface and base. In contrast to Carena et al. (2000, *J. Geophys. Res.* 105) we use a closed form solution of the linearized Reynolds' Equation. (3) The surface of the viscous layer is loaded by a normal stress (interpreted as being generated by a flexible solid strip load with free slip along its base) and its evolution is solved by making use of the so-called shallow-wave approximation (Janečka & Průša, 2014, *Int. J. Non-Linear Mech.* 60).

Irrespective of the nature of surface load, in the limit, i.e. as time approaches infinity, the final depth reached by the buoyant body must be consistent with Archimedes' principle (Figure 1). The positions of the substratum's surface at selected dimensionless times for the three considered approaches are illustrated in Figure 2. The results show that a 200 m thick rectangular load of half-length 500 m and buoyant density 1000 kg/m^3 placed onto a 500 m thick substratum with a linear viscosity of 10^{18} Pa s and buoyant density 1200 kg/m^3 has subsided to almost the asymptotic (Archimedes) limit after about 0.5 Ma. The local subsidence rates of the buoyant body depend, however, on the nature of the load: The rigid body exhibits, as expected, a uniform subsidence rate. Lubrication theory yields maximum subsidence rates at the edge of the body ($|x| = l$), whereas the strip load solution predicts maximum subsidence rates at the centre of the load ($x = 0$).

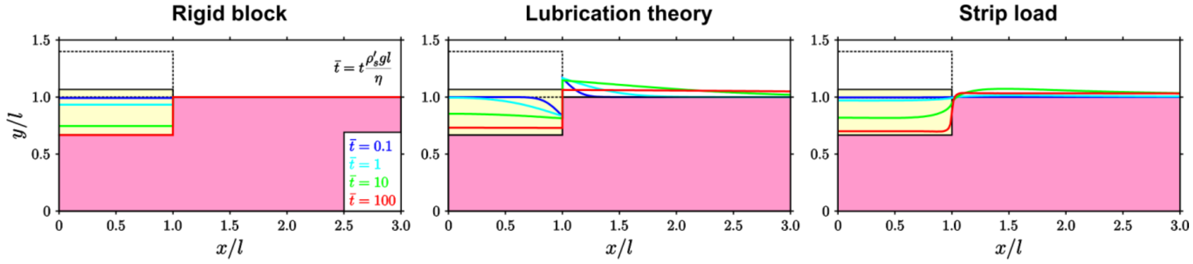

Figure 2. Positions of the viscous substratum's surface at four selected dimensionless times for the three considered solutions. Only the right hand side of the symmetric solutions are shown. The dashed rectangle is the load's outline at t = 0. Geometrical and mechanical parameters: Initial substratum thickness h_0 = 500 m; load thickness H_0 = 200 m; load half-length l = 500 m; substratum viscosity □= 10^{18} Pa s; buoyant density of substratum □'$_s$ = 1200 kg/m^3; buoyant density of load □'$_o$ = 1000 kg/m^3; gravitational acceleration g = 9.81 m/s^2 (the effective normal stress for the strip load solution is 2 MPa). The dimensionless times correspond to approx. 0.5, 5, 50 and 500 ka.

The normalized submerged volume of the load as a function of initial substratum thickness and dimensionless time is shown in Figure 3. These plots illustrate that the rigid block solution yields the largest subsidence rates since it assumes that the substratum adjacent to the load is under hydrostatic conditions, which is not the case for the other two considered solutions. Nevertheless, all solutions illustrate that subsidence rate increases non-linearly with increasing salt thickness. However, only the strip load solution asymptotically approaches a finite subsidence rate as the substratum thickness increases (i.e., it becomes identical to the solution for the loading of a viscous half-space).

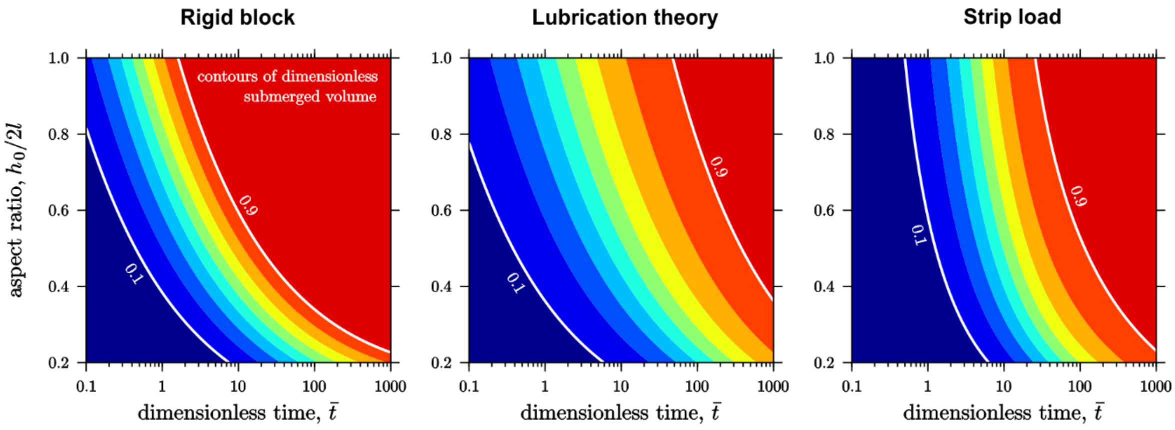

Figure 3. Contour plots of dimensionless submerged volume (submerged volume at a given time divided by finite submerged volume) as a function of initial substratum thickness (normalized by load width) and dimensionless time (as defined in Fig. 2) for the three considered solutions. The submerged volume is taken as the area above the substratum's surface and below the initial substratum level in the interval |x/l| ≤ 1. Geometrical and mechanical parameters as in Figure 2.

In this presentation we also introduce analytical solutions for more realistically shaped overburden loads that are built up gradually. These transient solutions yield the response of a viscous substratum to syn-sedimentary loading and hence provide a tool to estimate the sedimentation rates at which the system is approximately in its equilibrium state.

NOTES:

Investigating controls on salt movement in extensional settings using finite-element modelling

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Salt structures present numerous challenges for targeting reservoirs. Salt movement within the subsurface can follow complex pathways, producing deformation patterns in surrounding strata which are often difficult to decipher. Consequently, the relative role of key salt flow drivers and geological sensitivities on salt structure evolution are often poorly understood. To address this, we have developed 2D geomechanical models using the finite element method to simulate salt diapir and pillow development in two extensional tectonic settings. We conducted model sensitivity analyses to examine the influence of geological parameters on field-scale salt structures and their corresponding deformation pattern. Modelled diapirs developing in thin-skinned extensional settings closely resemble published analogue experiments, however active and passive stages of diapir growth are seldom or never reached, respectively, thus challenging existing ideas that diapir evolution is dominated by passive growth. In all modelled cases, highly strained domains bound the diapir flanks where extensive small-scale faulting and fracturing can be expected. Asymmetric diapirs are prone to flank collapse and observed in models with fast extension or sedimentation rates, thin roof sections or salt layers, or initially short or triangular shaped diapirs. In modelled thick-skinned extensional settings, salt pillows and suprasalt overburden faults can be laterally offset (decoupled) from a reactivating basement fault. This decoupling increases with increased salt layer thickness, overburden thickness, sedimentation rate and fault angle, and decreased fault slip rates. Contrary to existing consensus, overburden grounding onto the basement fault scarp does not appear to halt development of salt structures above the footwall basement block.

NOTES:

Applying State-of-the-Art 3D Geomechanical Forward Modelling to Problems in Salt Tectonics

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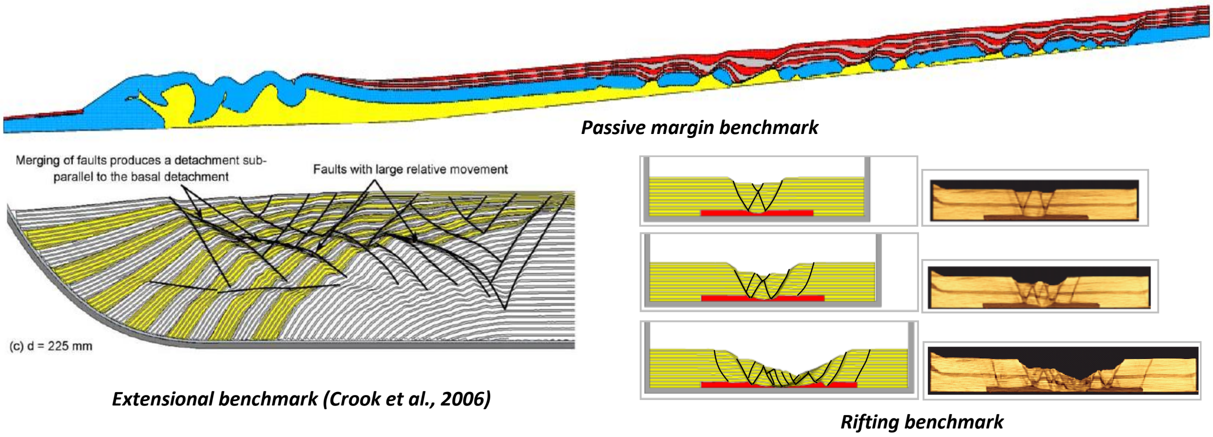
The presence of mobile salt formations is known to produce spectacular and complex structural configurations. This is largely because of the unique constitutive properties of salts, with salt creep rates being highly sensitive to differential stress and temperature. Capturing such behavior is critical to understanding the processes/mechanisms that have resulted in a particular structural style, and furthermore in constraining quantitative information that has relevance to industrial activities targeting salt structures. This talk aims to outline a state-of-the-art numerical framework for studying salt-induced deformation. The pre-requisites of the computational framework are outlined in the context of salt tectonics studies. Benchmark examples are shown to demonstrate the accuracy of the computational framework (Figure 1).



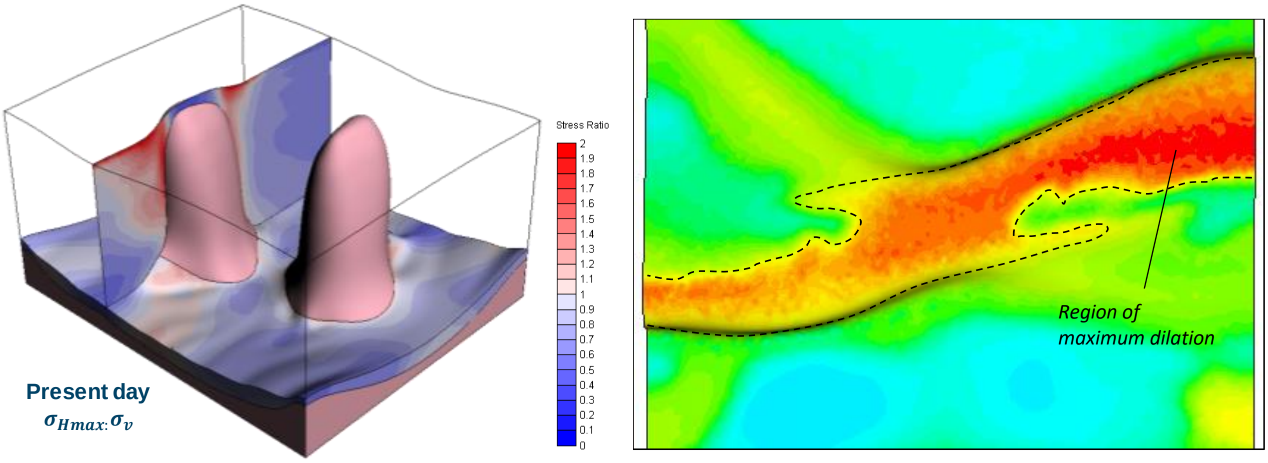
Passive margin benchmark

Extensional benchmark (Crook et al., 2006)

Rifting benchmark

Figure 1: Benchmarking of the computational framework

The numerical techniques are then applied to a selection of field scenarios reflecting different tectonic settings, initially in extensional and compressional environments. Emphasis is accorded to the requirement for moving away from 2D plane-strain representations due to the interplay between adjacent diapirs in extensional scenarios, or along strike variability of salt cored thrusts and anticlines in compressive settings (Figure 2).



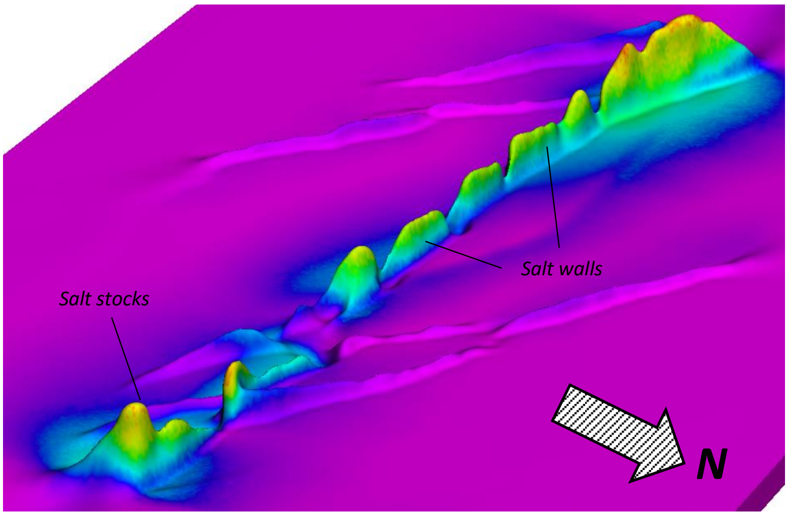
Extensional case: Forward modelled adjacent salt structures – present day effective stress ratios

Compressional case: Plan view of forward model output indicating volumetric changes in sediments within a WSE-ENE trending salt cored anticline

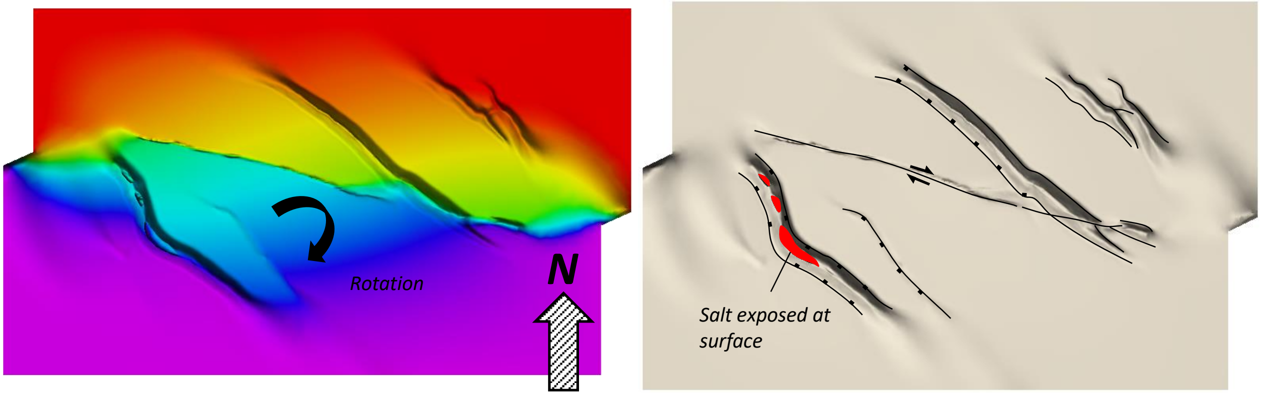
Figure 2: Application to salt studies in extensional and compressional environments

The requirement for 3D modelling is further emphasized by looking at salt behavior in transtensional stress environments where a complex juxtaposition of fault types and salt expression is observed (Figure 3); quite clearly it is difficult to reconcile such deformation conditions within 2D models.

Finally, numerical procedures for circumventing resolution limitations due to 3D modelling are explored. This involves submodelling strategies whereby displacement histories on areas of interest in large scale models are recorded and used as boundary conditions in smaller, higher resolution models. In this way "regional scale" deformation histories can be incorporated into "asset scale" submodels.



Transtensional case: Salt expression



Transtensional case: Surface displacements and fault distribution

Figure 3: Application to salt tectonics in transtensional settings

In all cases the insights and diverse quantitative information that can be derived from these physics-based models is demonstrated, and application to stress/pore pressure determination and reservoir/fracture characterization are outlined. Integration of such models into workflows using more conventional methods e.g. kinematic restoration, analogue modelling, is highlighted to be of significant benefit and the synergy between each of these tools warrants closer collaboration.

NOTES:

Revealing the control of salt tectonics on possible migration pathways by combining sea bed anomaly mapping and basin modeling

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Identification of sea bed anomalies such as; mud-volcanoes, sea mounds and depressions, is essential to restrict the vast offshore areas for to drill and to reduce the risks in the offshore exploration projects. As being a wild-cat region, the Mersin Bay area lacks sea bed studies focusing on the hydrocarbon seepage and its effects on the bathymetrical profile. This study aims to construct a robust relationship between sea bed anomalies and migration pathways using a recently acquired 3D seismic data. Seismic interpretation of the sea bed resulted with crucial discoveries of unprecedented 5 km long linear shaped sea mound and scattered mound-depression area that have been mapped for the first time (Fig.1).

Fig 1.

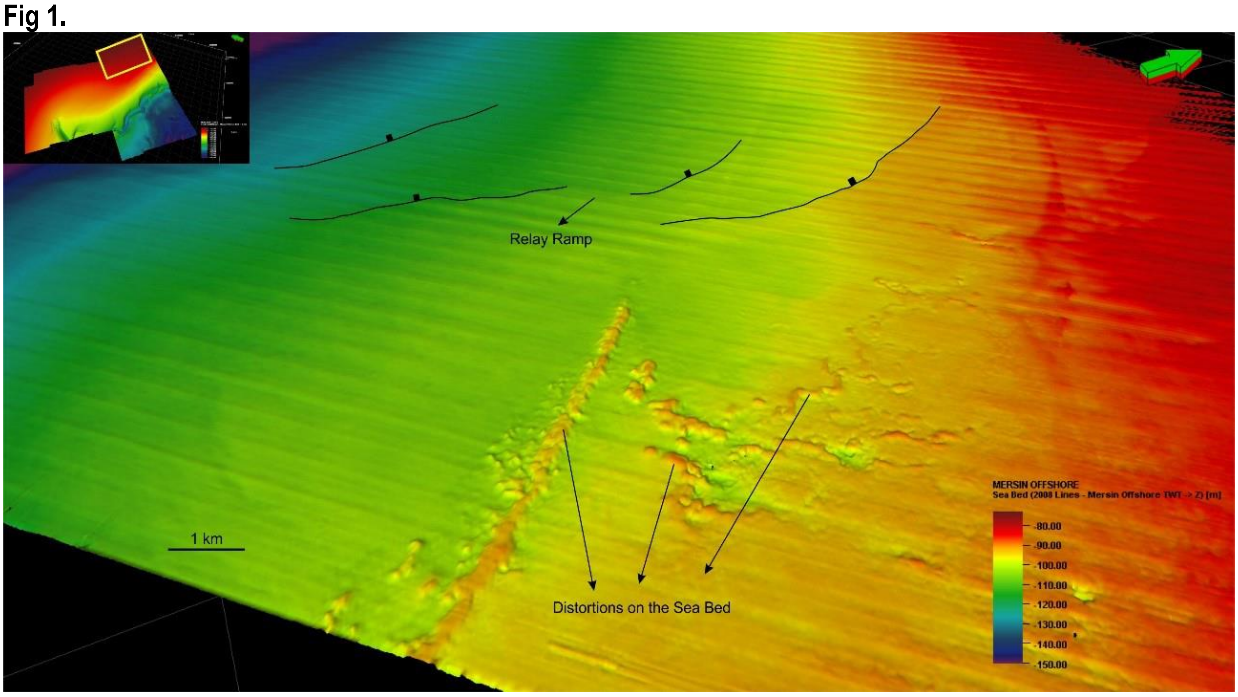

Fig 1. The 3D View of the sea bed anomalies

The findings suggest that sea bed anomalies are highly likely associated with the presence of shallow gas. However, the origin of gas is debateable due to the lack of robust geochemical data. Based on the existence of a Plio-Quaternary deltaic succession, biogenic gas is the most promising candidate while an additional thermogenic origin is unignorable. In order to test this hypothesis, source rock maturity maps have been created from two different geological levels as; Serravalian aged shales and Langhian aged marls. Both source rock levels remain in the pre-salt succession as the Messinian salt is seperating the Miocene and Plio-Quaternary sections. The maturity maps in the Mersin Bay, as the outcomes of basin modeling, suggest that an elipsoidal kitchen area is present, especially at the NNE part of the region (Fig.2-A-B). According to the vitrinite reflectance values depicted on the maturity maps, Serravalian aged, submarine fan shales are in the oil window while Langhian aged marls are in the gas window, generating since the end of the Messinian Salinity Crisis.

A migration pathway issue emerges if pre-salt thermogenic origin for the shallow gas anomalies is a fact. The main restriction for the vertical migration is the presence of the Messinian salt. A risk map, derived from the maturity and salt thickness maps, highlights the potential vertical and lateral migration pathways (Fig.2-C). Elongated zones, following the listric normal fault strikes, represent the salt welded areas where a vertical migration can develop into the Plio-Quaternary section. On the other hand, lateral migration is a significant possibility in the region as Al-Balushi et al. (2016) have proposed a similar scenario in the Levant Basin. The possibility is also supported by pore pressure profiles. A pore pressure cube, generated from interval velocities, has been reflected on the seismic sections (Fig.2-D). Pressure trends have shown that the Messinian salt acts as a pressure boundary between the Plio-Quaternary aged supra-salt section and the Early-Middle Miocene aged pre-salt succession (*Uyanik, 2018*). The profile suggests that a lateral migration might occur from overpressured zone into low pressured, young sediments. Moreover, sea bed anomalies and deltaic sediments located on the route of migration are characterised by bright spot anomalies, supporting the lateral migration hypothesis. (Fig.2-C-D).

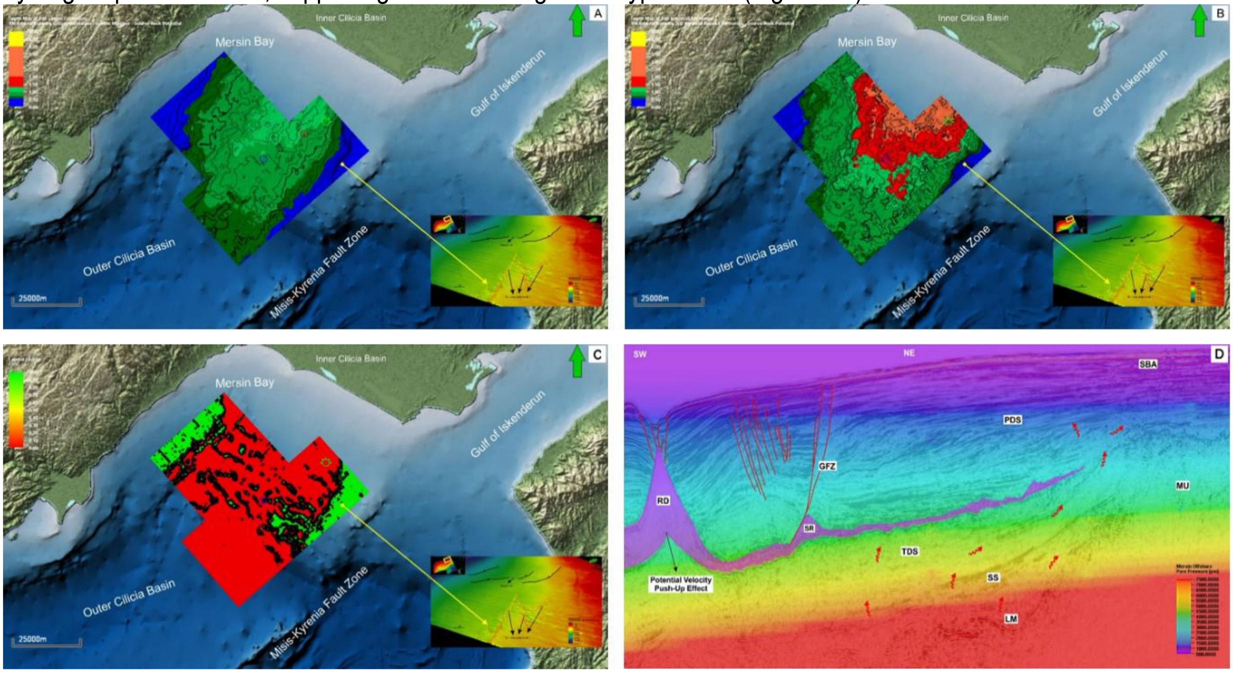

Fig 2. Images summarising the basin modeling and pore pressure analysis results
(**A:** Serravalian shales maturity map, **B:** Langhian marls maturity map, **C:** Risk map for migration pathways, **D:** Reflected view of pore pressure cube on 2D seismic data)

As a conclusion; the effect of the possible gas seepage on the sea floor, characterised by mounds and depressions, indicates a working hydrocarbon system. The origin of the shallow gas is thought to be biogenic, however, basin modeling studies have shown that hydrocarbons generated from a deeper thermogenic source might have contributed to the process as the sea bed anomalies and bright spots are located directly on the eastern migration pathway. A satelite image analysis has supported that possibility by revealing oil slicks on the sea surface, corresponding directly to the sea bed anomaly region (*Karacay et al., 2017*). Nevertheless, the lack of well data penetrating such depths in the area makes the presence of generating Miocene aged source rocks hypothetical, leading to the necessity of further geochemical research. Therefore, sea floor sampling and imaging should be conducted to obtain certain results for the origin of potential shallow gas with an additional oil-slick sampling from the sea surface as a supplementary research.

NOTES:

From salt rock physics to depth imaging: Seismic forward modelling of Levant and West-Sardinia basins.

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The Messinian Salinity Crisis (MSC) was a short-term (5.96-5.33Ma) and dramatic paleoenvironmental event, which led to the deposition of a thick evaporitic layer throughout Mediterranean area. However, several studies have demonstrated that Messinian evaporites have different characteristics from East to West in the Mediterranean area, and the Caltanissetta Basin (Sicily, West Mediterranean) provides a rare and excellent Messinian onshore record for investigating the evaporitic succession. Given the scarcity of representative halite samples and, at the same time, widespread research and scientific drilling in the Mediterranean area, new petrophysical insights of the Messinian halite are important for the understanding of the seismic response of the MSC sequence and the production of improved imaging of salt structures. Hence, 50 samples of Messinian halite were obtained from a Sicilian mine (Italkali), analyzed and tested using different instruments, in order to measure physical, mechanical, petrophysical, mineralogical, and thermal properties.

Ultrasound velocities measured under hydrostatic confining pressure up to 120 MPa, ranged from 4210 to 4780 m/s and 2510 to 2650 m/s, respectively, for P- and S-waves; halite densities have been measured with the hydrostatic weighing method and gas-porosimeter, showing low values ranging from 2.14 to 2.23 g/cm3. Consequently, Vp and density measured values have been used as input for two seismic forward modeling simulations related to western and eastern sector of Mediterranean Basin. From analysis of polarity characteristics we highlighted the changes in lithology, and polarity reversal is evident at gypsum/clastic or halite/clastic contact, rather than in the expected halite/gypsum contact. Moreover, the observed ranges in measured Vp allows to estimate the range of differences of halite thickness between the synthetic model construction the experimental seismic data.

The comparison between synthetic and field seismic data revealed to be useful tool for seismic data interpretation, as well as to validate geological models especially in complex systems such as salt-driven tectonic provinces.

NOTES:

Large-transport thrusts in salt bearing fold and thrust belts: Insights from analog modeling & comparison with case studies

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It has been large demonstrated, that salt is a first order controlling factor on the structural style of fold and thrust belts (eg. Pyrenees, Betics, Atlas, Alps, Zagros, etc…). In fact, it acts as a strain localizer being a very effective contractional detachment that constraints basement-detached or thin-skinned deformation. In this scenario, buckling and thrusting are common, but also the development of new diapirs, the reactivation of the inherited ones, or salt extrusion forming salt sheets. The main parameter controlling buckle folds is the thickness ratio between salt and overburden. According to that, folding usually dominates faulting, with the development of symmetrical folds, no consistent structural vergence and high-angle reverse faults. Nevertheless, this structural style could be strongly modified by syn-contractional sedimentation that can focus deformation in certain structures that accumulate huge shifts. This is the case of large-transport thrusts with a net slip of 10 km or more. These structures have been described in different salt-bearing fold-and-thrust belts (eg. Cotiella and Montsec thrusts in the Pyrenees; Dinar thrust in the Zagros; Quele thrust in the Tarim Basin; the Chazuta thrust in the sub-Andean Huallaga basin or the Salt Range thrust in the Potwar Plateau among others).

This work utilizes scaled physical (sandbox) models to investigate what are the main factors that controls the development and kinematic of large-transport thrusts in saltbearing fold-and-thrust belts. In order to depict which are the control parameters as well as the role of each one, four experiments have been run with variations on overburden and salt thickness, and syn-contractional sedimentation. The experimental rig includes two fixed glass-sided walls and two metal end walls, one fixed and the other moved by a servomotor-driven warm-screw controlled by computer at a constant velocity of 5 mm/hour (32 cm total shortening). A basal layer of silicone polymer (5 or 15 mm-thick depending on the experiment) was used to simulate the viscous behaviour of salt. Well-sorted rounded dry quartz sand (199 µm average grain size) was poured in alternating white and colored layers simulating the brittle behaviour of brittle rocks in nature. Depending on the experiment the thickness of the pre-compressional overburden was 15 mm or 30 mm. The syntectonic 4º-dipping wedge was simulated pouring twelve layers of 10 mm thick after 30 mm shortening. The experimental results show strong differences on the wavelength of the detachment folds depending on salt and overburden thicknesses ratio (Fig. 1). Thus, thin salt or thin overburden favour the formation of small wavelength folds. In these experiments, the limb rotation of the salt-cored anticlines located at the edge of the salt basin forms injection folds with crestal erosion that favour salt piercement developing diapirs (Fig. 1a). When this occurs, the confined salt rapidly depressurizes and extrudes forming wide salt sheets (Fig. 1a). The frontal limb of the injection fold is usually trapped below the sheet after salt breakout forming an overturned flap (Fig. 1a). In contrast, thick salt favours inflation, developing longer wavelength folds (Fig. 1a and 1c). The size and volume of these salt sheets will be higher as thicker is the polymer layer. On the other hand, the development of large-transport thrust is favoured by thick overburden that confines the polymer during the whole experiment without extruding salt sheets (Fig. 1c). When this occurs, a source-fed thrust nucleates at the salt basin-edge and is active until the end of the experiment accumulating large slip. Another key factor in the development of large-transport thrust is the syn-contractional sedimentation (Fig. 1d).

During the early stages of shortening, syn-kinematic sedimentation forces salt inflation near the edge of the salt basin, but as shortening increases the salt inflated area broken developing a large-transport thrust that localizes and absorbs subsequent deformation. For extreme shortening, the feeder located at the edge of the basin pinched-off and can be reactivated as a thrust weld.

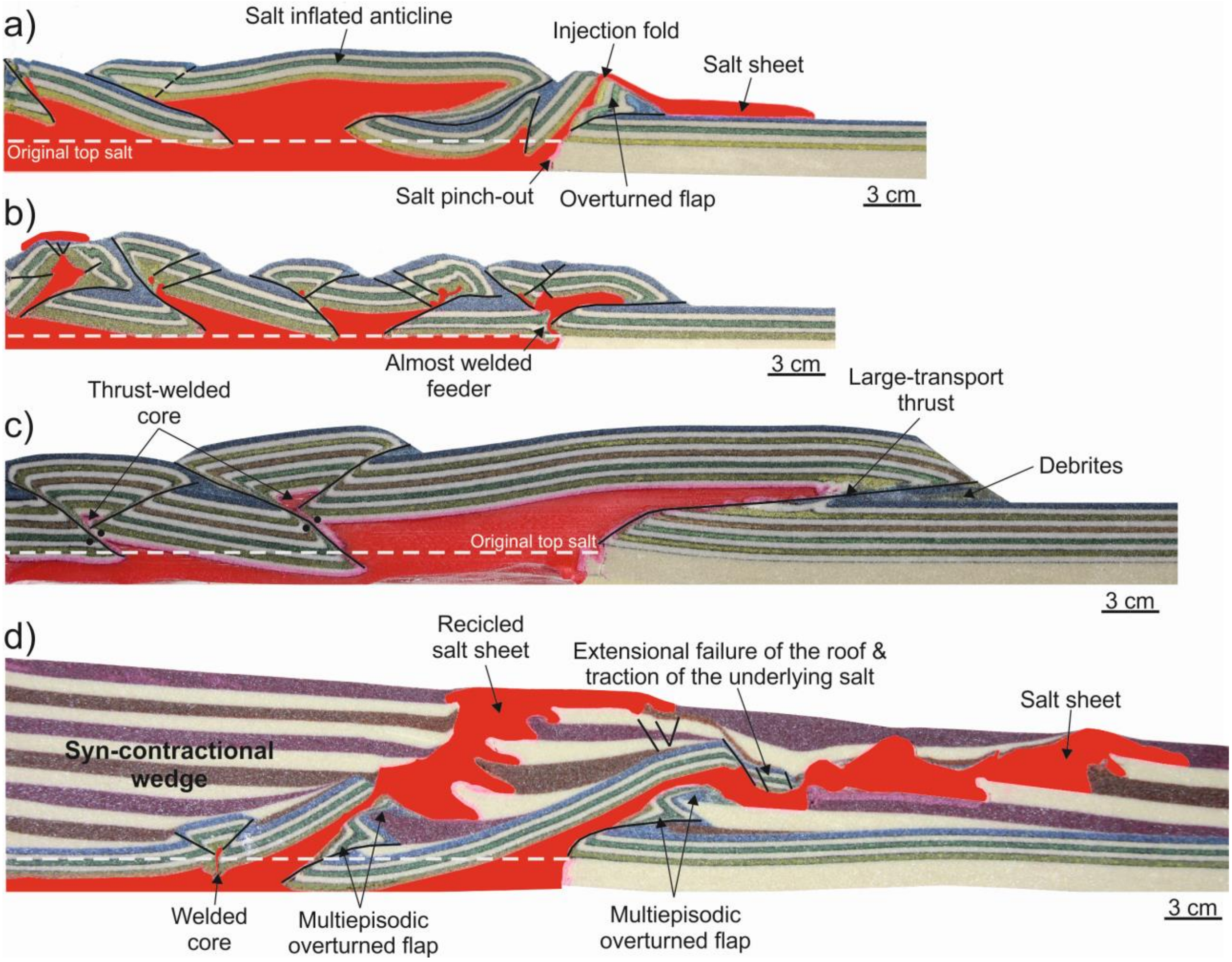

Figure 1.- Interpreted central cross-section of the different experiments showing the different structural style controlled by the modeled factors (polymer in red). a) Thick polymer and thin pre-contractional overburden; b) Thin polymer and thin pre-contractional overburden; c) Thick polymer and thick overburden; and d) Thick polymer and thin pre-contractional overburden with syn-contractional sedimentation.

Finally, the kinematic evolution of the experimental results are discussed and compared with different natural examples of salt-bearing fold-and-thrust belts with large-transport thursts. In addition the physical models also provide structural criteria to apply during the interpretation of these structures poorly imaged in seismic.

NOTES:

Best practice structural modelling and kinematic algorithms used for validation and restoration in salt basins

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When carrying out structural analysis, selection of an inappropriate algorithm can result in misinterpretation of the shape and location of hydrocarbon traps. Reservoirs in salt-related basins can be incredibly complicated, making them very challenging to interpret and understand. At the margins of salt structures there often exists a large degree of uncertainty in the seismic interpretation of the salt-sediment contact and in the shape and internal structure of the reservoir. If this uncertainty is not properly understood it can lead to inaccurate volumetric calculations and problems with well placements. However, it can be reduced using structural modelling techniques.

Geometric restorations, for instance performing a 3D jigsaw fitting to identify gaps or overlaps around a diapir, can be used to assess the validity of interpretations. This can lead to significant improvement of interpretation at the margins of salt structures. Sequential restoration workflows, which reverse the effects of geological processes, make possible to determine hydrocarbon trap development and investigate basin architecture through time. Structural analysis can improve confidence in the hydrocarbon play and has wide application, for example for facies modelling or strain-based natural fracture prediction.

Here, we will review the recommended workflow for geometric and sequential restorations of salt structures, which involves: using appropriate back-stripping techniques to restore physical compaction, isostasy and post-rift thermal subsidence; restoring supra- and sub-salt faulting; and, using unfolding algorithms to restore the effects of salt movement on supra-salt sediments. A key advantage of the workflow is that it can be performed quickly, allowing different scenarios to be rapidly tested and evaluated, eliminating those that are unfeasible or inconsistent with the data.

We will use a series of synthetic and natural examples from the Gulf of Mexico and the North Sea to assess the implications of using different algorithms and techniques for geometric and sequential restorations. In particular, we will focus on the differences caused by using simple shear or flexural shear unfolding algorithms to restore the effects of salt movement. The geological, displacement and strain implications for modelling the deformation with each algorithm will be assessed. We will demonstrate that the selection of simple shear can lead to incorrect gaps and restored geometries during a restoration, with significant implications for planning decisions.

NOTES:

Day three: Session Six - Halokinetics

New mapping of El Gordo Diapir and sedimentary architecture of halokinetic sedimentary sequences (ancient outcrop case study in northeast Mexico)

Ramon Lopez Jimenez
geologist consultant

El Gordo diapir (Nuevo Leon, Mexico) is one of the best exposed case studies worldwide of an ancient salt diapir with associated halokinetic sedimentary sequences. Recent geological mapping of the boundaries of El Gordo Diapir shows remarkable differences over former published maps (e.g. Rowan et al., 2003). The new geological map points to the existence of, at least, two extrusive diapir flanges that separate three halokinetic sequences of sandstone dominated deposits. Carbonate deposits have been found overlying these flanges but also as well-preserved tabular beds into the central part of the diapir exposures.

The sedimentary architecture of the halokinetic sedimentary sequences located to the SW side of the diapir have been examined in detail for the first time. This architectural analysis shows that the interpreted mini-basin that was promoted on this side of the diapir evolved from purely depositional to a mix of erosional and depositional character.

On the other hand, there is evidence in the field of the fundamental role of a propagation thrust, at least during the first phase of the diapir growth. Mapped tectonic structures and geometry of strata terminations fit in a case type of a thrust weld as a result of the squeezing of a relatively dormant diapir.
These and other corrections over former geological maps change the previous geological model of El Gordo diapir and the mini-basin stratigraphic sequence, and thus its appropriate use as outcrop analogue.

Figure 11. Panorama of two of the best exposed halokinetic sequences that rapidly taper to the diapir wall (to the right-centre). Credit: Ramon Lopez Jimenez

NOTES:

Four-dimensional Variability of Halokinetic Sequence Architecture

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The stratigraphic architecture of salt diapir-flank strata (i.e. halokinetic sequences) is controlled by the interplay between volumetric diapiric flux and sediment accumulation rate. Halokinetic sequences consist of unconformity-bounded packages of thinned and folded strata formed by drag-folding around passive diapirs. These sequences are described by two end-members: (i) *hooks*, which are characterized by narrow zones of folding (<200 m), high-angle truncations (>70°) beneath bounding unconformities, and abrupt facies transitions towards the salt-sediment interface; and (ii) *wedges*, which are typified by broad zones of folding (300-1000 m), low-angle truncations (<30°) beneath bounding unconformities, and gradual facies changes towards flanking salt. Hooks and wedges stack to form tabular and tapered composite halokinetic sequences (CHS), respectively. CHS were first and have been most thoroughly described from outcrop-based studies that, although able to capture their high-resolution facies variations, are limited in terms of describing their 4D variability. This study integrates 3D time- and depth-migrated seismic data from the SE Precaspian Basin, onshore Kazakhstan and structural restorations to examine variations in CHS architecture through time and space along a series of diapirs with variable plan-form and cross-sectional geometries. Diapirs range from semi-circular stocks to 5-15 km long curvilinear walls that vary from upright to inclined in cross-section, may flare-upward, locally display well-developed salt shoulders or laterally transition into salt rollers. CHS architecture is highly variable in both time and space, even along a single diapir or minibasin. For example, a single CHS can transition or change abruptly along a salt wall and/or minibasin from tabular to tapered geometries and, in places, they can also extend far (>600 m) up the sides of diapirs or, in the case of salt shoulders, be downturned. In the case of inclined salt walls, they commonly vary laterally from a dominant tabular geometry at their centre to tapered outwards. In terms of the vertical stacking, CHS can present a typical succession of lower tapered, intermediate tabular and upper tapered sequences, but also unique patterns where the lower CHS are tabular and grade upward to tapered CHS. The same CHS can also vary across a single salt diapir being tabular in one minibasin and tapered in the other. The study demonstrates that CHS architecture is more variable than previously thought, indicating a complex interplay between salt rise, diapir geometry, roof thickness and sediment accumulation along salt walls, something not previously captured in 2D models. Ultimately, this improves our current understanding of diapir-flank deformation and potential reservoir distribution and pinch-out.

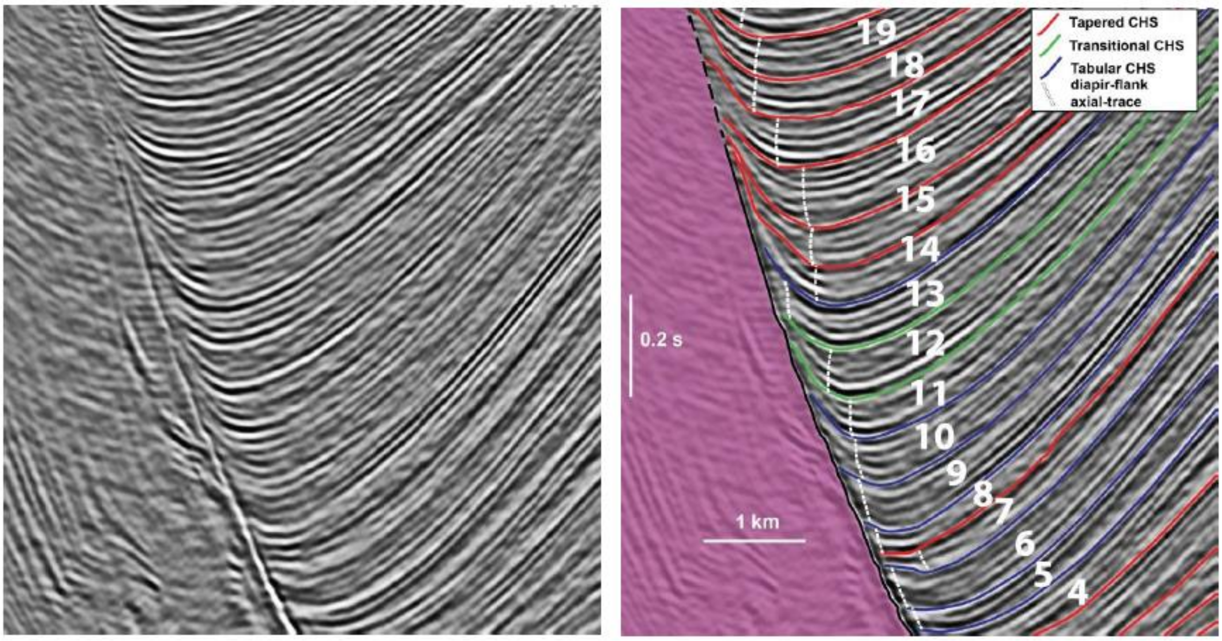

Figure 1: Uninterpreted and interpreted seismic section demonstrating the seismic character, drape-fold geometries and vertical variability of composite halokinetic sequences (CHSs) along an inclined salt wall onshore

Precaspian. Tabular CHSs are characterized by narrow (< 200 m) zones of drape-folding and abrupt upturn and Tapered CHSs by broader (> 300 m) zones of folding. Salt cusps typically form at the salt-sediment interface associated preferentially with the unconformities bounding tabular CHSs.

NOTES:

Halokinetic Controls on the Evolution of Shallow Marine Facies Architecture: Insights from the Upper Jurassic Fulmar Formation, United Kingdom Continental Shelf

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Salt kinematics has the potential to modify basin subsidence and create topographic barriers to sediment transport. As documented examples of halokinetically-influenced siliciclastic shallow marine environments are sparse, the sedimentary architecture of such deposits remains poorly understood. Therefore, in order to understand halokinetic controls on facies distribution and reservoir quality within and between salt-withdrawal minibasins it is important to conduct a detailed study of subsurface data.

The Upper Jurassic Fulmar Formation of the Central North Sea provides an ideal opportunity to study the effects of halokinesis on shallow marine sediments. The succession was deposited into salt-wall collapse basins formed by the dissolution of mobile Zechstein salts. The geographical distribution and facies of the formation were controlled by the complex interplay of basin-scale tectonics, active salt migration and dissolution. The presence of numerous closely spaced well penetrations and continuous 3D seismic data enable a detailed interpretation of the subsurface. Focus is given to interpreting the spatial and temporal distribution of facies within and between salt withdrawal basins, relating this where possible to varying rates of subsidence and sedimentations produced as a result of active salt dissolution.

In this work we have integrated ichnofabric, sedimentological, wireline and biostratigraphical data with 3D seismic data from the Central North Sea. Initial results indicate that the gross depositional environment of the sediments and therefore the associated facies distribution remains unaffected by the continued dissolution and movement of Zechstein salts. Indeed the development of salt collapse structures may act solely to preserve thickened packets of sediment from later episodes of erosion.

This work will clarify the importance of halokinesis, sediment supply and subsidence upon facies distribution, producing predictive depositional models of facies distribution and connectivity that are applicable to the Fulmar Formation and similar salt-influenced, shallow marine sediment hydrocarbon plays.

NOTES:

Calibrating the kinematics of a thick salt sheet using fluid escape pipes and natural strain markers

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We present a study that demonstrates how gas venting above large pre-salt anticlinal traps can be used to help unravel the kinematics of a thick salt sheet during gravity driven deformation. Using high resolution 2D and 3D seismic reflection data from the Levant Basin in the Eastern Mediterranean, we identify 5 linearly distributed trails of fluids escape pipes with pockmarks at their upper terminus. These fluid escape pipes emanate from lower Miocene reservoirs within pre-salt anticlinal traps and cross over 3 km of stratigraphy, including the thick (>1 km) Messinian salt. The pockmarks at the upper terminus constrain the timing of fluid expulsion and are distributed NW-SE, orthogonal to the basin margin. The first expulsion episode in each linear pipe trail was synchronous, dated at 1.7 Ma (±0.3 Ma), which is approximately synchronous to the onset of basinward salt flow from the basins eastern margin 1.8 Ma. The pockmarks sequentially young to the SE and the oldest pockmark in each trail is offset 3.4 - 8 km NW from the crest of the pre-salt structure. A localised, high amplitude and continuous reflection extends obliquely through the salt beneath each pipe trail, connecting the oldest pockmark to the crest of the pre-salt fold.

We interpret this obliquely dipping anomalous reflection in the salt as a deformed fluid escape pipe. We show that the originally vertical configuration of the pipe was titled by the flow of the salt over the last 1.7 Ma. The geometry of the deformed fluid escape pipes demonstrates a Couette flow regime through the salt. The episodic fluid expulsion episodes above the pre-salt structures were systematically offset NW by basinward salt flow. The orientation of these pipe trails therefore presents a direct kinematic indicator for the flow direction of the salt during its most recent phase of deformation. The flow of the salt is unidirectional over a region > 50 km in the translational/contractional domain, but with changes in cumulative strain (3.4 - 8 km) and velocity (2 – 4 mm/yr) over distances of only a few km. Despite expected contracts in flow regime between extensional and contractional domains, cumulative heave measurements from the extensional domain projected in line with the pipe trails approximately balance with cumulative strain in the translational/contractional domain. This has significant implications for the flow regime between extensional and contractional domains and demonstrates the potential in using fluid escape features to understanding salt kinematics.

NOTES:

Halokinetically influenced deep-water successions; examples from seismic scale outcrops

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Deep-marine successions onlapping salt diapirs form combination structural-stratigraphic traps and can be excellent quality reservoir intervals. Typically, these halokinetic sequences are poorly-imaged in seismic data, due to steep dips, salt overhangs and near-diapir deformation. In addition they are not well represented in outcrop, largely due to dissolution of the associated halites. The facies and architecture of these halokinetically influenced deep-marine successions are therefore poorly-understood but are anticipated to differ from those in unconfined basins, or those with static topography.

The Triassic (Keuper) Bakio and Guernica salt bodies in the Basque-Cantabrian Basin, Spain, are rare exhumed salt structures with associated deep-marine successions. The structures grew reactively, then passively, during the Aptian-Albian and are flanked by deep-marine Aptian-earliest Albian carbonates and middle Albian-Cenomanian siliciclastics. The exhumed halokinetic sequence to the west of the Bakio Diapir (Figure 1) shows shallowing and younging of stratigraphy and unconformities away from the diapir. These seismic-scale outcrops enhance understanding of sub-seismic scale facies variability and deformation at the salt-sediment interface. Extensive exposure in the mini basin between the two salt structures provides a rare opportunity to study salt-sediment interactions where palaeoflow is at a low angle to structural strike, compared to the better documented 'fill and spill'. The deep-water siliciclastic succession shows upwards coarsening, thickening of beds and reduction of fines. The lower mudstone-rich succession is dominated by thin-beds and hybrid beds, interpreted as distal fringe deposits. These gradually increase in sandstone percentage and bed thickness upwards, into stacked, amalgamated high-density turbidites interpreted as proximal lobe deposits. The inferred allocyclic progradation is heavily modified by salt growth with slumps, and other soft-sediment deformation, hybrid beds and debrites developed in response to topographic growth of the sea bed. Facies vary significantly between the mini basins developed on either side of the diapir.

These outcrop findings are combined with subsurface data from the twin diapiric Pierce Field, eastern Central Graben, UK North Sea and a 2D discrete element model to enhance understanding of the multi-scalar influence of halokinesis on deep-water systems. The Palaeocene Forties Formation reservoirs at Pierce Field show remobilised, injected deposits and stratigraphic pinch-out approaching the diapirs. Sedimentologically compartmentalised reservoirs and highly variable reservoir quality were partly responsible for the prolonged time gap between initial discovery and first oil. The models illustrate the variety of configurations

possible in salt-influenced deep-water successions and can be used conceptually to understand the interplay of controlling factors, and guide seismic interpretation in salt-influenced basins.

The integration of these techniques allows for the spatial and temporal distribution of deep-water facies in salt-influenced basins to be recognised. In most deep-water successions the dominant controls are allocyclic, but these successions are heavily influenced by halokinesis which drives autocyclic modulation of the primary signal.

The results are directly applicable to petroleum exploration and development, geothermal and carbon capture and storage industries in salt basins globally, enabling better prediction of trap geometry and reservoir quality and distribution, in areas where seismic imaging is challenging.

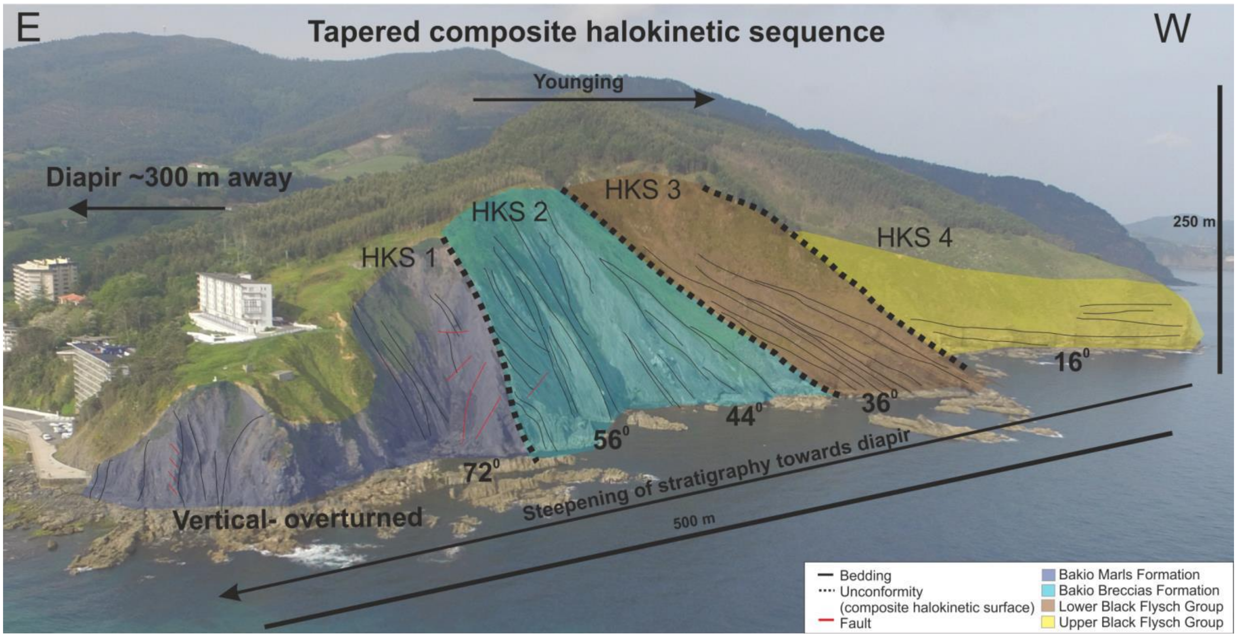

Figure 1: Drone photograph of halokinetic sequence on the west of the Bakio Diapir. Stratigraphic section shallows and youngs away from diapir, beds closest to the diapir are overturned. Individual wedge halokinetic sequences are bound by progressive unconformities, which shallow away from the diapir. The Bakio Diapir has a tapered composite halokinetic sequence ~500 m wide which shows high levels of facies variability and deformation. HKS 1; Halokinetic Sequence 1.

NOTES:

Syn-halokinetic carbonate platforms and clastic deltas: 3D seismic examples offshore Gabon

Paolo Esestime, Karyna Rodriguez and Neil Hodgson
TGS

Shallow water offshore Gabon is part of an extensive salt province on the eastern Atlantic Margin, where mobile evaporites have controlled carbonate and clastic deposition. Halokinesis was particularly active during the Upper Cretaceous, when salt related structures influenced both local subsidence and sediment supply. The hypersaline deposits were developed during the initial phases of marine transgression, and are characterised by sodium-potassium rich evaporites with intervals of halite and gypsum (Ezanga Formation), followed by persistent shallow marine carbonates (Madiela Formation). Since the Cenomanian-Turonian, the carbonate environments were gradually replaced with deltaic systems.

3D seismic data acquired in 2017-2018 with long 8000m offset and processed through modern broadband and depth imaging algorithms, has successfully targeted the post-rift sequences, as well as the pre-evaporitic syn-rift.

In South Gabon, halokinesis was initiated in a low relief shelf. The deposition of shallow water carbonates initiated with extensive tabular bodies (sequence s1), frequently interbedded with the underlying transgressive Vembo Shale Formation. During the halokinesis, tabular carbonates were replaced by a series of smaller salt-related local atolls, each with their own shelf around the diapirs, (sequence S2) (Figure 1). These were then gradually engulfed in larger turtle-structures and rafts. Seaward tilting occurred from the Late Cenomanian-Turonian, when most of the evaporites had already withdrawn, resulting in marginal reactivation of pre-existing structures. Subsequently, a more stable substratum allowed the development of a widespread carbonate platform over the inboard areas, and created an extensive shelf controlled by regional bathymetry (sequence s3) (Figure 1).

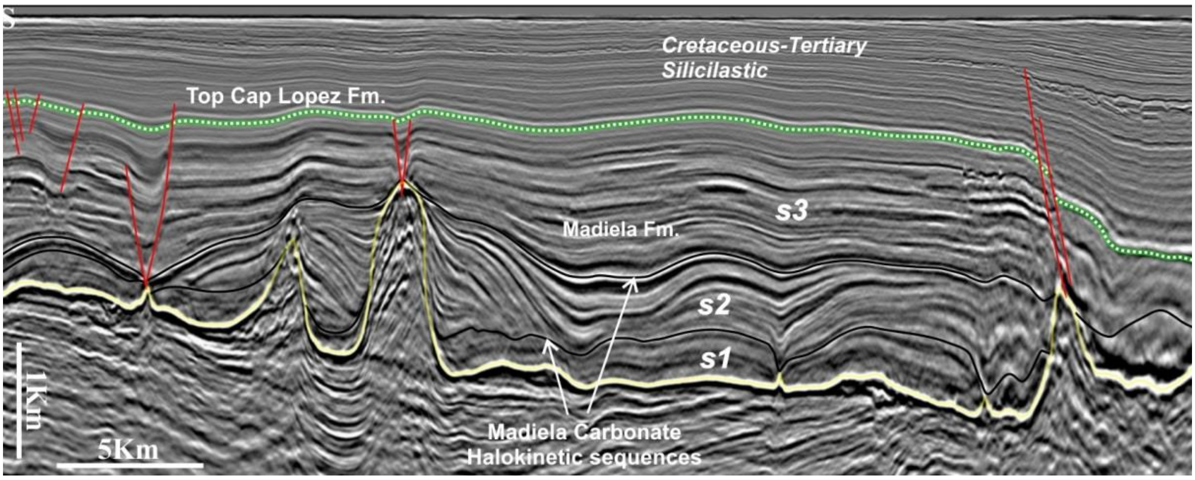

Figure 1 Gabon South 3D. Kirchhoff Pre-Stack Depth Migration resuming the main shallow carbonate sequences identified in the Madiela Formation: s1, tabular units, s2, carbonate atolls; s3, regional platform.

Seismic velocity analysis, combined with well data, suggests diffuse pelagic Madiela carbonate. Clastic input almost completely replaced the carbonates since the Cenomanian-Turonian, developing a deltaic system, which gradually moved seaward to the west. The salt diapirs diverted the sediment supply, and large channelized bodies were discharged around depocenters created by salt walls and overhangs. A regional shelf wasn't completely developed until the salt gradually subsided (Oligocene and the Miocene).

In contrast to the south, in North Gabon halokinesis initiated when extensional faults were active, as is suggested by the several hundreds meters of offset at the base of the evaporites. Halokinesis took place on a substratum with high relief and active faults, and a highly variable paleo-bathymetry. Salt movement remained active from the Late Cretaceous through to the Paleogene, controlling the subsidence and sediment supply within local minibasins, in part or completely overlapped by allochthonous salt nappes, which were gradually pushed and deflected outward, to the deep water, following the sediment loading of the deltaic systems.

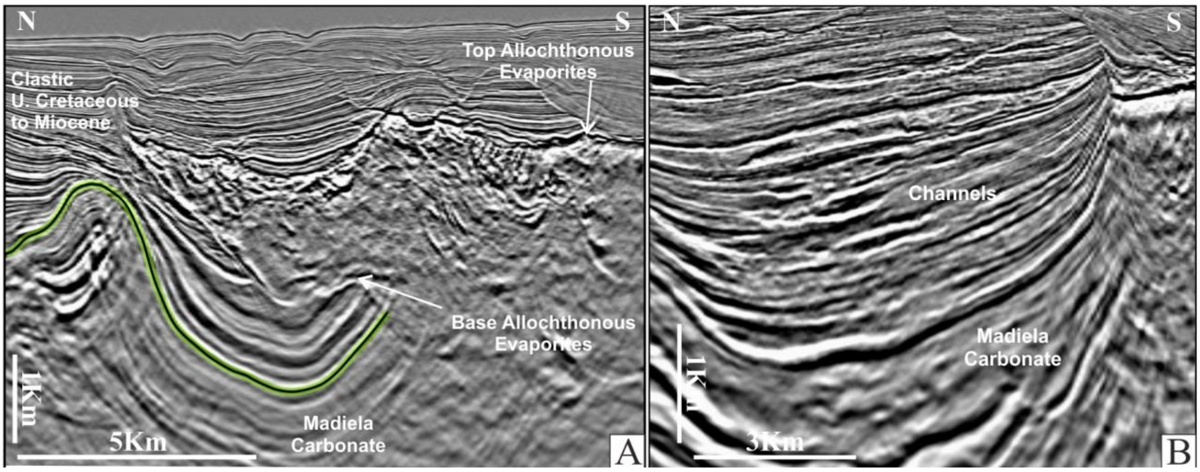

Figure 2A) and 2B) are Kirchhoff Pre-Stack Depth Migration. Section A) shows the extensive salt overhangs, overlapping the autochthonous salt, Albian Carbonate and Upper Cretaceous siliciclastic deposits. B) Clastic deltaic deposits organized in channelized bodies surrounding the salt structures.

NOTES:

Posters

Semi-automated fault mapping beneath a regional salt layer using seismic attributes and raster tracing techniques

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Regional mapping of faults in the subsurface, using standard manual 3D seismic interpretation methods, can be a highly time-consuming task, regardless of the geological setting. Seismic attributes can help detect structural discontinuities, which may not be clearly visible in seismic amplitudes alone, aiding the interpretation process and drastically reducing the amount of work and time required. However, in sedimentary basins containing significant amounts of halite, which has undergone structural deformation, edge detection attributes do not always allow to resolve the pre-salt faults with a fair level of certainty. Edge enhancement algorithms can prove helpful in this case. This study proposes an alternative approach for quick, semi-automated regional mapping of subsurface faults using edge detection and edge enhancement attributes in combination with raster tracing techniques.

Dataset and methodology

The dataset used in this study consists of a subset of the Southern North Sea MegaSurvey basin-scale 3D seismic dataset provided by Petroleum Geo-Services (PGS) containing four 3D seismic volumes from the Sole Pit, Inde Shelf and Cleaver Bank areas of the Southern North Sea, covering a total area of c. 11,640 km2. The workflow steps included: 1) computation of the similarity attribute in the Kingdom software (Fig. 1b) using a large calculation window to attenuate noise and improve the horizontal resolution; 2) ant tracking attribute computation (Petrel software) in two runs: first, using variance attribute as input (computed here as 1.5-similarity), next, using the ant track result as input to enhance the discontinuity information (Fig. 1c). To reduce a chance of picking up artefacts at the edges of seismic surveys, all nearly vertical events in the inline and crossline directions were filtered out; 3) vector tracing of a georeferenced ant track raster map using ArcGIS software (Fig. 1d).

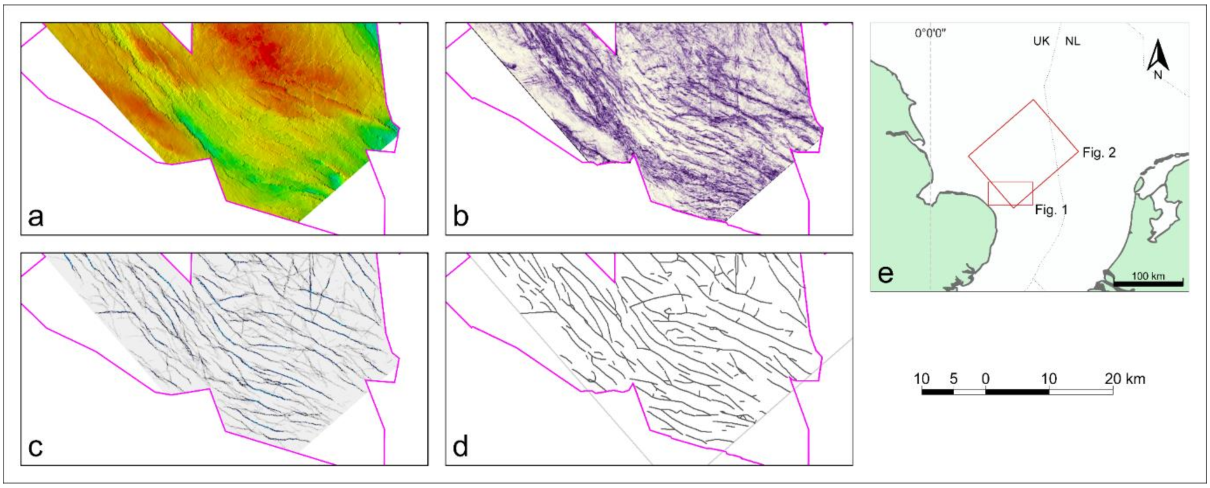

Figure 12: Structural maps of the top of pre-salt section horizon from the southern and south-eastern part of the Sole Pit High, Southern North Sea; a) Structure-TWT map, red-shallower, green-deeper, horizon illumination from west; b) similarity attribute computed using a very large similarity window (240 ms, i.e. 60 times the value of seismic sampling). Purple indicates zones of low similarity values; c) ant tracking attribute computed in two runs: (1) using variance attribute as input (1.5-similarity), (2) using the ant track attribute from run (1) to suppress small scale structures and enhance large faults. Grey to blue colours indicate zones of discontinuity; d) faults traced using raster tracing techniques on ant track raster map as input; e) location map. Red boxes correspond to areas shown in figures 1 and 2.

The resulting polyline dataset was further used for a regional analysis of fault orientations. Additionally, for the quality check of the results, the outlines of salt structures were mapped using vertical seismic sections as well as smoothed dip of maximum similarity attribute and TWT maps of the top of salt horizon in the Kingdom software. The outlines of salt structures are shown in Fig. 2a.

Results and discussion

The imaging of the base of salt horizon is strongly affected by velocity pull-up effects (Fig. 1b), which “leak” into the similarity attribute along the edges of salt structures, making it impossible to map the actual trajectories of the pre-salt faults. The ant tracking attribute helps resolve more structural details beneath and in the vicinity of salt structures (Fig.1c). A sharp definition of the ant-tracked discontinuities in a map view provides a proper input for semi-automated interpretation using raster tracing. Traced faults (Fig. 2a) reveal a slightly bimodal strike distribution with a clear dominant NW-SE strike direction and a weaker NE-SW trend (Fig. 2b).

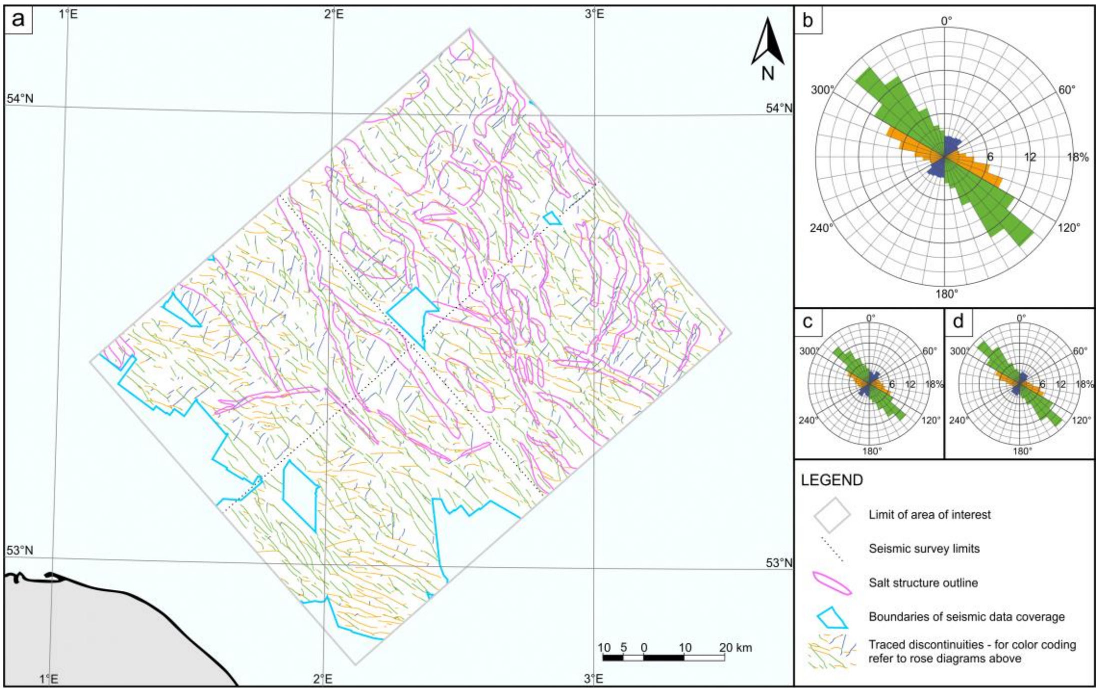

Figure 13: Top of pre-salt fault orientation: a) fault distribution map showing faults traced using raster tracing techniques, color-coded according to strike direction, as in diagrams in b-d. Salt structure outlines are shown in pink for reference; rose diagrams of: b) all traced faults, c) faults traced below salt structures, c) faults traced below surrounding depocenters, limited to c. 20 km from salt structures. Location shown on map in Fig. 1e. Observations include: similar orientation patterns below and away from salt structures, largely oblique to overlying salt structures; slightly bimodal strike distribution (dominant NW-SE direction and secondary NE-SW direction); fair to good definition of faults below and along edges of salt structures.

The validity of the method is supported by two rose diagrams (Fig. 2c-d) calculated separately for faults located beneath salt structures and below the surrounding depocenters, limited to c. 20 km away from the salt structures. Both diagrams reveal similar geometries implying that the obtained fault dataset is not significantly affected by salt velocity pull-up effects along salt structures, which in most part of the area trend oblique to the basement faults. The limitations of the method include: poor data quality (also resulting from structural complexity, intensive halokinesis, and depth of observation), “wash-out” areas along the edges of seismic surveys due to filtering (Fig. 2a), acquisition footprint and linear data edge artefacts producing “false faults” in ant track volumes.

Conclusions

The proposed method allows to produce regional fault distribution maps in a relatively short amount of time, also below salt diapirs and walls and beneath surrounding depocenters. The resulting dataset can quickly provide information on fault distribution and strike orientation at a regional level.

Diapirism in the Betic-Rif Foreland: The Wedge-Top Basins of the SW Iberian and NW Moroccan Margins. Preliminary results.

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The SW Iberian (SWIM) and NW Moroccan (NWMM) Margins' evolution results from an intricate interplay between tectonic, sedimentary and paleoceanographic processes. The close proximity of these margins to the Eurasian-African plate boundary and the Betic-Rif Orogeny resulted in a complex tectonic evolution (e.g. Duarte et al., 2013; Zitellini et al., 2009). The westward migration of the Betic-Rif domain emplaced a massive chaotic body of deformed Mesozoic to Cenozoic strata in the Gulf of Cadiz region during the Late Tortonian. This body comprises the Gulf of Cadiz Accretionary Wedge (GCAW) and the related gravitationally driven Allochthonous Unit. Salt (Triassic evaporites) and shale diapirism (Miocene muds) has been recognised in the SWIM and NWMM, which was supplied by the GCAW and the Allochthonous Units (e.g Medialdea et al., 2009). Several mud volcanoes and other fluid escape features were also recognised along both margins.

Late Miocene-Quaternary wedge-top basins developed on top of the accretionary wedge, the Doñana, Sanlucar and Cadiz Basins in the SWIM and the Offshore Gharb Basin in the NWMM. The sedimentary infill of these basins, strongly controlled by diapiric activity, comprises different depositional systems (e.g. turbidites, mass transport deposits, contourites and pelagic/hemipelagic sediments). The aim of this work is to evaluate how regional tectonic structures and diapirism affected the development of the wedge-top basins, and to establish the similarities and differences between the two margins. This is accomplished with the seismic analysis of high quality regional multichannel seismic reflection profiles and well data.

Extensive diapiric activity is recorded in the wedge-top domain basins. The diapiric structures are characterized by chaotic seismic facies with steep flanks that are rooted in the GCAW. Several small-scale faults and folds related to diapiric activity occur either on top of or adjacent to the flanks of the diapiric bodies or ridges. Sediment loading caused the vertical migration of salt, which led to the formation of minibasins. These minibasins are characterised by synclinal infill with differential folding indicating syn-tectonic sedimentation. This demonstrates the occurrence of several pulses of diapiric vertical migration. Shortening is inferred from the tilting of some of the minibasins. The shifting of basin depocenters is an important factor in their evolution, particularly in the NWMM. Sedimentation exceeded accommodation space in the minibasins causing widespread deposition along the margin. This widespread sedimentation covers older minibasins as well as reliefs generated by the diapiric activity. Most of the diapiric structures mapped along the SWIM and NWMM do not crop out on the present-day seafloor. Nevertheless, some of the larger diapiric features and related mud volcanoes do, indicating Quaternary activity.

In the SWIM the most important features are the NE-SW Doñana and Guadalquivir Ridges and the N-S Cadiz Diapiric Ridge. Both the Guadalquivir and Cadiz Ridges largely affect the present-day bathymetry. In the NWMM, one ridge was observed with a WNW-ESE orientation. These ridges are roughly parallel to the Betic-Rif orogenic front, indicating that tectonic forces related with the convergence of the Betic-Rif domain controlled diapirism in the Gulf of Cadiz region. The inherited margin structures in the SWIM, (e.g. Guadalquivir Basement High) conditioned the advancement of the GCAW, which led to intense compression of the wedge-top domain. In the NWMM, the wedge-top domain appears to be strongly influenced by the dextral strike-slip SWIM faults (Duarte et al., 2011; Zitellini et al., 2009). The orientation of the diapiric structures and the location of the mud volcanoes could be related to these tectonic features as they show an identical orientation. Higher intensity of diapiric activity was observed in the SWIM, where extensive diapiric ridges outcrop on the present-day seafloor, separating the wedge-top domain into three main basins.

Diapirism influenced the Late Miocene-Quaternary wedge-top basins by manipulating the basin depocenters and the margin morphologies. In the SWIM, the diapiric structures controlled the pathways and intensities of bottomcurrents and thus the evolution of the well-known Gulf of Cadiz Contourite Depositional System. In the NWMM, contouritic deposits are not as well established, but they can be observed locally alongside bathymetric reliefs such as diapiric bodies and mud volcanoes. These bathymetric reliefs could also have an influence on turbiditic events by confining flow pathways and creating slope instability which consequently causes mass transport deposits.

This work demonstrates that the combined regional compressional setting and active diapirism significantly controlled the structure and evolution of the SW Iberian and NW Moroccan Margins during the Late Miocene-Quaternary. The presence of inherited margin structures and the Quaternary transpressional regime governed the evolution of the GCAW in the Betic-Rif foreland. Consequently, it controlled the development of diapiric features and depositional architectures of both margins.

Acknowledgements: D.D. thanks the FCT (Fundação para a Ciência e Tecnologia) for the PhD scholarship (reference SFRH/BD/115962/2016). This project is partially funded by the Joint Industry Project supported by TOTAL, BP, ENI, ExxonMobil, and Spectrum and partially supported through the CGL2016-80445-R (AEI/FEDER, UE), CGL2015-66835-P and CTM2016-75129-C3-1-R. The research studies are conducted in the framework of 'The Drifters Research Group', Department of Earth Sciences, Royal Holloway University of London (UK).

The Esperança Diapiric Ridge: Late Miocene-Quaternary compressional reactivation of a Salt Nappe in the Eastern Deep Algarve Basin, SW Iberian Margin

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The development of the SW Iberian Margin since the Late Miocene is a result of an intricate interplay between tectonic, sedimentary and paleoceanographic processes. It has undergone a complex tectonic evolution related to the Betic-Rif Orogenic Arc and its proximity to the Eurasian-African plate boundary. As a result of the westward migration of the Betic-Rif domain, a massive chaotic body composed of deformed Mesozoic to Cenozoic strata was emplaced during the Late Tortonian within the Gulf of Cadiz (the Gulf of Cadiz Accretionary Wedge, GCAW and the Allochthonous Unit of the Gulf of Cadiz, GCAU). The Esperança Salt Nappe is a large allocthonous salt canopy emplaced in the Eastern Deep Algarve Basin (SW Iberian Margin) between the Guadalquivir Bank structural high and the present-day shelf-break. It developed between Middle Jurassic to Early Cretaceous (Matias et al., 2011; Ramos et al., 2017) and comprises Triassic evaporites. The late Miocene-Quaternary sedimentary infill of the Deep Algarve Basin is composed of a Miocene turbiditic-hemipelagic sequence influenced by the adjacent Guadalquivir Basin (Ledesma, 2000), and Pliocene-Quaternary contourite deposits developed under the influence of the Mediterranean Outflow Water (MOW) (Hernández-Molina et al., 2016). The aim of this work is to understand the effect of the regional compressional setting on pre-existing diapiric structures in the Deep Algarve Basin since the late Miocene, and how it influenced the sedimentary evolution of the margin. This has been accomplished from an in-depth analysis of high quality regional multichannel seismic reflection profiles, and a chronological framework and lithological information from well data.

The NE-SW oriented Esperança Diapiric Ridge was observed to the northeast of the Guadalquivir Bank structural high. The seismic units on top of the diapiric ridge suffered local deformation with the development of small-scale faults and folding of the late Miocene-Quaternary sequence. The intensity of the folding decreases upwards and has no expression on the present-day seafloor. Four pulses of diapiric activity can be identified, based on unconformities separating the seismic units with different degrees of deformation: Late Miocene-Pliocene, Pliocene-Middle Pleistocene and Middle Pleistocene-Present. This diapiric feature was developed where the GCAW/GCAU was able to overcome the Guadalquivir structural high and entered the Deep Algarve Basin. We propose that the shortening resulted from the emplacement of the GCAW which led to the squeezing of the pre-existing salt nappe and the formation of the Esperança Diapiric Ridge with a roughly parallel orientation to the front of the GCAW/GCAU. Thus, this diapiric ridge is also approximately parallel to other ridges formed on the GCAW domain, such as the Doñana and Guadalquivir Diapiric Ridges. This reflects a control by tectonic forces related to the convergence of the Betic-Rif front with the SW Iberian margin.

The bathymetric relief formed by the diapiric ridge and the GCAW front influenced the growth patterns and the morphology of the SW Iberia Margin and controlled the accommodation space and depocenters of the Eastern Deep Algarve Basin between the Late Miocene to Quaternary. During the Late Miocene, these structures confined the pathways for gravitational processes and caused the formation of turbiditic channels within the valleys between them. The onset of the MOW circulation since the Pliocene-Quaternary saw the deposition of contourites in regions of locally reduced accommodation space that were affected by syn- or post-depositional folding of the diapiric ridge.

This work demonstrates the importance of GCAW related deformation on the Late Miocene-Quaternary evolution of the Eastern Deep Algarve Basin. The regional compressional setting, that caused the emplacement and later deformation of the GCAW, conditioned the structural development of the basin. Consequently, it controlled the development of diapiric structures, the turbidite and contourite depositional systems and their sedimentation stacking patterns.

Acknowledgements: D.D. thanks the FCT (Fundação para a Ciência e Tecnologia) for the PhD scholarship (reference SFRH/BD/115962/2016). This project is partially funded by the Joint Industry Project supported by TOTAL, BP, ENI, ExxonMobil, and Spectrum and partially supported through the CGL2016-80445-R (AEI/FEDER, UE), CGL2015-66835-P and CTM2016-75129-C3-1-R. The research studies are conducted in the framework of 'The Drifters Research Group', Department of Earth Sciences, Royal Holloway University of London (UK).

Impact of early salt tectonic processes on post-Permian Basin evolution and Mesozoic petroleum systems in the Southern North Sea

Christopher Brennan, Anna Preiss, Jürgen Adam, Nicola Scarselli
Royal Holloway, University of London

Early post-Permian salt tectonic processes, their regional tectonic controls and their relationship with varied palaeo-depositional systems were a major controlling factor of the post – Permian basin evolution of the North Sea but their trigger mechanisms and impact on Mesozoic basin architecture have not been systematically studied, yet.

This study utilises the Southern North Sea MegaSurvey basin-scale 3D seismic dataset provided by Petroleum Geo-Services (PGS) for the systematic identification, classification and kinematic analysis of Triassic-early Jurassic salt structures and related mechanisms of early salt mobilisation (Figure 1). These mechanisms include (1) coupled gravity thin-skinned extension and contraction starting in the Triassic forming reactive diapirs, salt walls and salt cored anticlines, (2) Triassic - early Jurassic halokinesis forming salt pillows and passive diapirs as well as (3) reactive salt mobilisation related to extension during Mesozoic rifting and contraction during late Mesozoic-Cenozoic inversion stages.

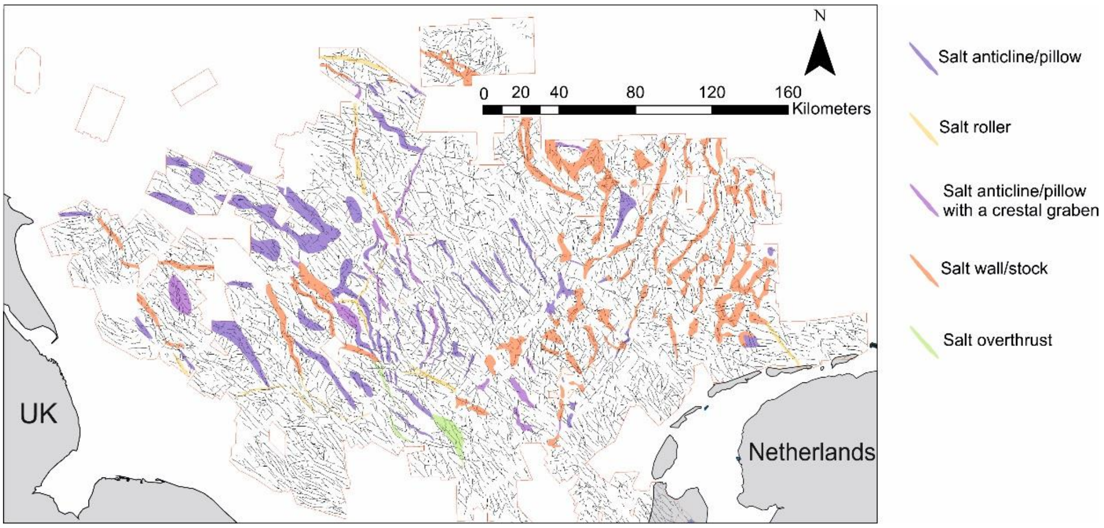


Figure 1: Regional map highlighting the different types of salt structures in the Southern North Sea according to their geometry, derived from smoothed dip of maximum similarity attribute maps, regional transects and time structures maps.

Regional high resolution isochron maps have been generated to derive the onset of salt mobilisation and timing of salt structures in the Southern North Sea by examining thickness variations in the Triassic to Miocene overburden. Regional isochron maps show large packages of Triassic and Jurassic sediment with varying thickness in the Southern Central Graben because of reactive diapirism possibly related to the Cimmerian extension. In the northern Sole Pit High isochron maps show synkinematic Triassic and Jurassic sediment associated with reactive diapirs caused by thick-skinned extension. Early Mesozoic sediments are absent on the Cleaver Bank High however more research is needed to determine whether this is due to erosion related to the Base- Cretaceous unconformity or lack of Triassic and Jurassic depositions. Therefore, early salt mobilisation does not appear to begin until the mid-Cretaceous onwards which deforms supra salt strata. NW-SE regional transects illustrate thick-skinned extension with Jurassic minibasin formation in the Sole Pit Hight while the Dogger Shelf is an area of thin-skinned Triassic extension.

Maps illustrating the timing of salt mobilisation throughout the Southern North Sea have been created in order to highlight earliest and latest phases of salt activity throughout the basin. Figure 2 highlights the onset of salt mobilisation throughout the Southern North Sea. This map shows the majority of salt mobilisation in the Southern

North Sea began in the Triassic except for the Cleaver Bank High and northern Silverpit basin which began in the Jurassic and Cretaceous.

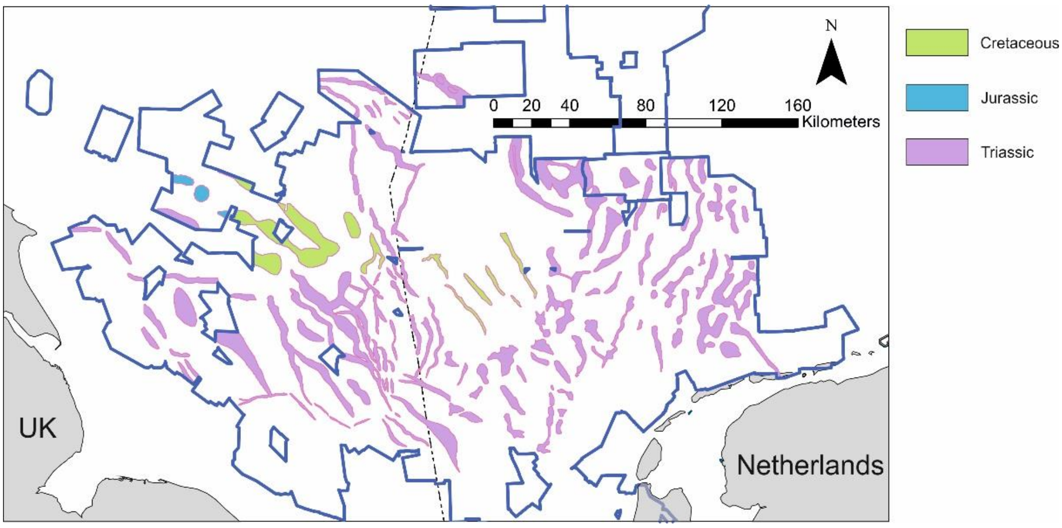


Figure 2: Regional map illustrating the timing of the onset of the salt mobilisation in the Southern North Sea. This map was created using a combination of regional transects and regional isochron maps to analyse thickness variations in the overburden which indicate periods of salt mobilisation.

Figure 3 illustrates the latest phase of salt mobilisation across the Southern North Sea which appears to be dictated by the amount of salt available and position within the basin. Salt structures in the Silverpit Basin and Sole Pit High are active for shorter amount of time possible due to much thinner salt in these areas and lack of accommodation space for Cenozoic sediments.

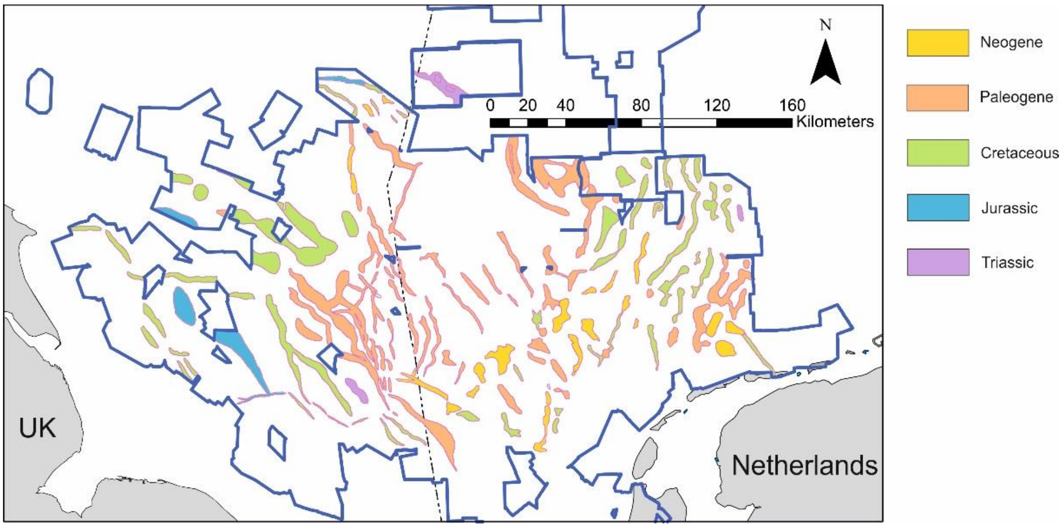


Figure 3: Regional map illustrating the conclusion of salt mobilisation in the Southern North Sea. This map was created using the same methods as Figure 2.

Improved understanding of these early salt tectonic processes will provide new insights into fundamental salt basin forming processes and mechanisms while developing new exploration strategies in the Mesozoic succession in mature North Sea basins.

GSL CODE OF CONDUCT FOR MEETINGS AND OTHER EVENTS

INTRODUCTION

The Geological Society of London is a professional and learned society, which, through its members, has a duty in the public interest to provide a safe, productive and welcoming environment for all participants and attendees of our meetings, workshops, and events regardless of age, gender, sexual orientation, gender identity, race, ethnicity, religion, disability, physical appearance, or career level.

This Code of Conduct applies to all participants in Society related activities, including, but not limited to, attendees, speakers, volunteers, exhibitors, representatives to outside bodies, and applies in all GSL activities, including ancillary meetings, events and social gatherings.

It also applies to members of the Society attending externally organised events, wherever the venue.

BEHAVIOUR

The Society values participation by all attendees at its events and wants to ensure that your experience is as constructive and professionally stimulating as possible.

Whilst the debate of scientific ideas is encouraged, participants are expected to behave in a respectful and professional manner - harassment and, or, sexist, racist, or exclusionary comments or jokes are not appropriate and will not be tolerated.

Harassment includes sustained disruption of talks or other events, inappropriate physical contact, sexual attention or innuendo, deliberate intimidation, stalking, and intrusive photography or recording of an individual without consent. It also includes discrimination or offensive comments related to age, gender identity, sexual orientation, disability, physical appearance, language, citizenship, ethnic origin, race or religion.

The Geological Society expects and requires all participants to abide by and uphold the principles of this Code of Conduct and transgressions or violations will not be tolerated.

BREACH OF THE CODE OF CONDUCT

The Society considers it unprofessional, unethical and totally unacceptable to engage in or condone any kind of discrimination or harassment, or to disregard complaints of harassment from colleagues or staff.

If an incident of proscribed conduct occurs either within or outside the Society's premises during an event, then the aggrieved person or witness to the proscribed conduct is encouraged to report it promptly to a member of staff or the event's principal organiser.

Once the Society is notified, staff or a senior organiser of the meeting will discuss the details first with the individual making the complaint, then any witnesses who have been identified, and then the alleged offender, before determining an appropriate course of action. Confidentiality will be maintained to the extent that it does not compromise the rights of others. The Society will co-operate fully with any criminal or civil investigation arising from incidents that occur during Society events.

Burlington House
Fire Safety Information

If you hear the Alarm

Alarm Bells are situated throughout the building and will ring continuously for an evacuation. Do not stop to collect your personal belongings.

Leave the building via the nearest and safest exit or the exit that you are advised to by the Fire Marshal on that floor.

Fire Exits from the Geological Society Conference Rooms

Lower Library:
Exit via main reception onto Piccadilly, or via staff entrance onto the courtyard.
Lecture Theatre
Exit at front of theatre (by screen) onto Courtyard or via side door out to Piccadilly entrance or via the doors that link to the Lower Library and to the staff entrance.
Main Piccadilly Entrance
Straight out door and walk around to the Courtyard.

Close the doors when leaving a room. **DO NOT SWITCH OFF THE LIGHTS**.

Assemble in the Courtyard in front of the Royal Academy, outside the Royal Astronomical Society. Event organizers should report as soon as possible to the nearest Fire Marshal on whether all event participants have been safely evacuated.

Please do not re-enter the building except when you are advised that it is safe to do so by the Fire Brigade.

First Aid

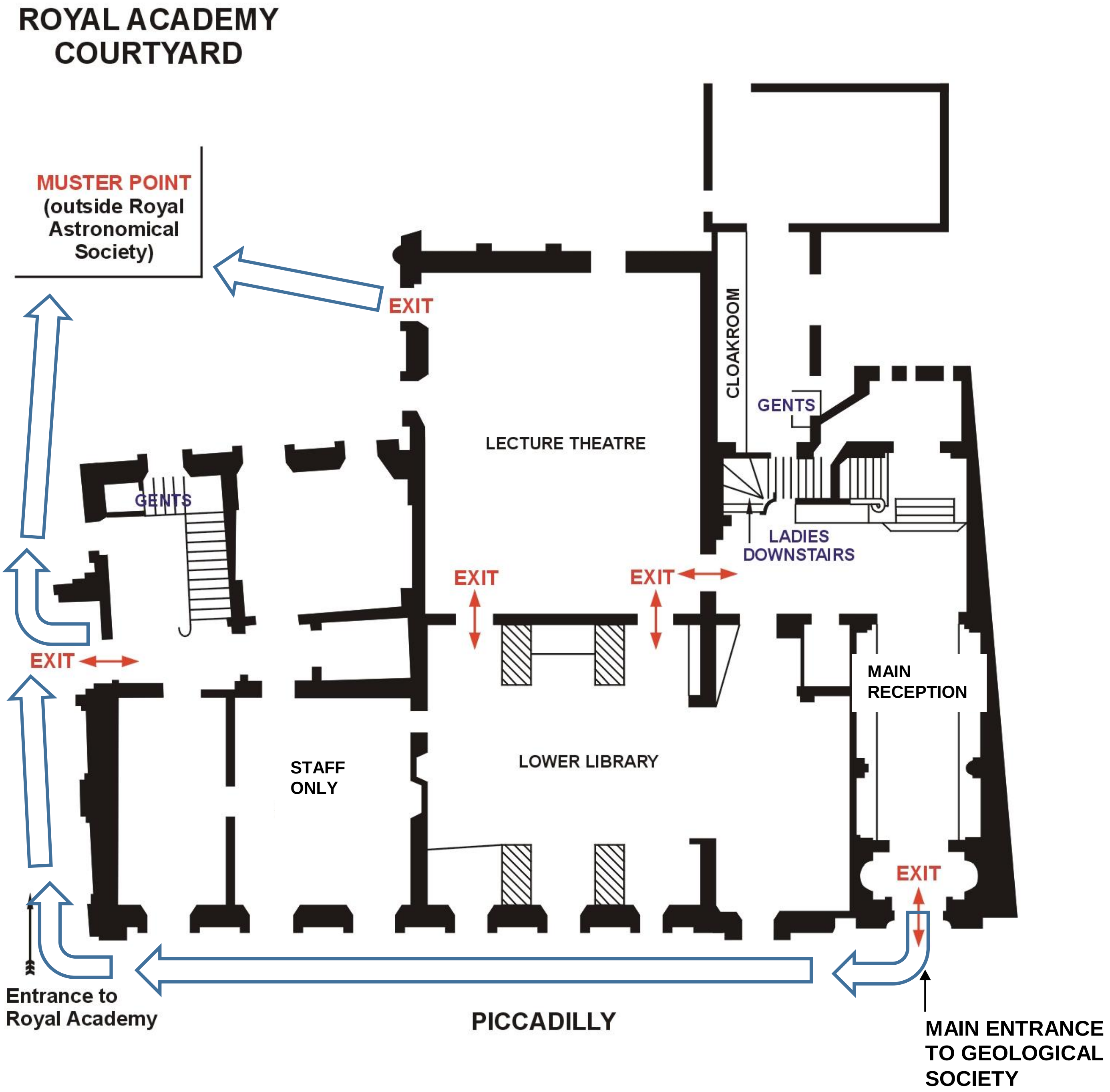
All accidents should be reported to Reception and First Aid assistance will be provided if necessary.

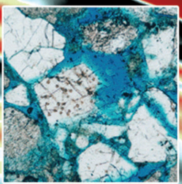
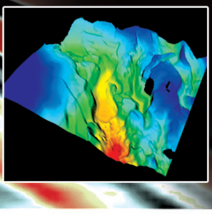
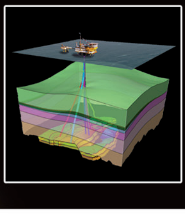
Facilities

The ladies toilets are situated in the basement at the bottom of the staircase outside the Lecture Theatre.

The Gents toilets are situated on the ground floor in the corridor leading to the Arthur Holmes Room.

Ground Floor Plan of the Geological Society, Burlington House, Piccadilly



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Call for Abstracts: Deadline 6 December 2019

Geopressure 2020

Managing Uncertainty in Geopressure by Integrating Geoscience and Engineering

24-26 March 2020

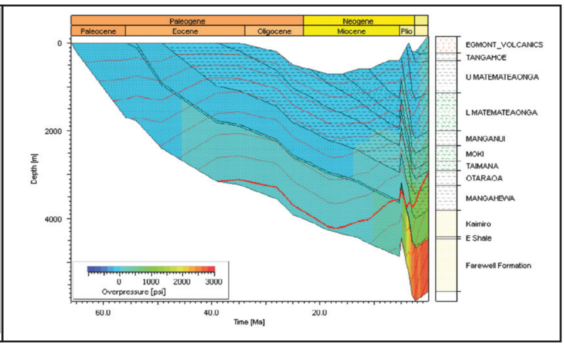
Durham University, Durham UK

24 March 2020: Field trip

Led by Richard Swarbrick and Jack Lee to North Yorkshire

25 and 26 March 2020: Conference

Durham University, UK



The organisers invite contributions within any aspect of geopressure but are particularly interested in the various phases of pore fluid pressure prediction, modelling and overpressure evaluation to manage uncertainty during the life cycle of a well. Suggested themes and sessions include:

- Pore Pressure and stress, especially complex stress regimes
- Impact of machine learning on PPFG
- Well engineering and PPFG
- Injecting fluids underground (including CO2)
- Coupling of Pore Pressure and FG including depletion and closing the drilling window
- Seal capacity and relationship with PPFG
- PPFG issues in mature basins (including abandonment/decommissioning)
- Classic case studies, including Macondo and LUSI mud volcano
- Pore pressure as an exploration and prospectivity tool.
- Geopressure in mature basins – lessons learnt
- Pore pressure in active tectonic basins
- Unconventional stress regimes

Further Information and abstract submissions:

To submit an abstract please send it to abstracts@geolsoc.org.uk and copy to sarah.woodcock@geolsoc.org.uk.

For more information please contact sarah.woodcock@geolsoc.org.uk or visit the event website: www.geolsoc.org.uk/PG-Geopressure-2020

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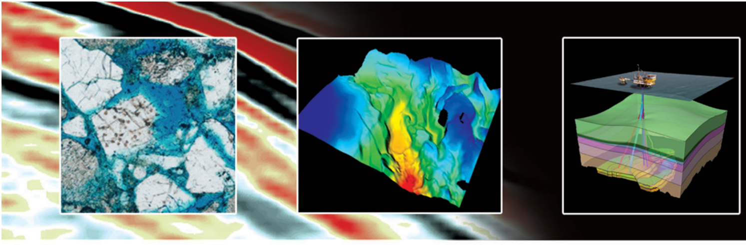

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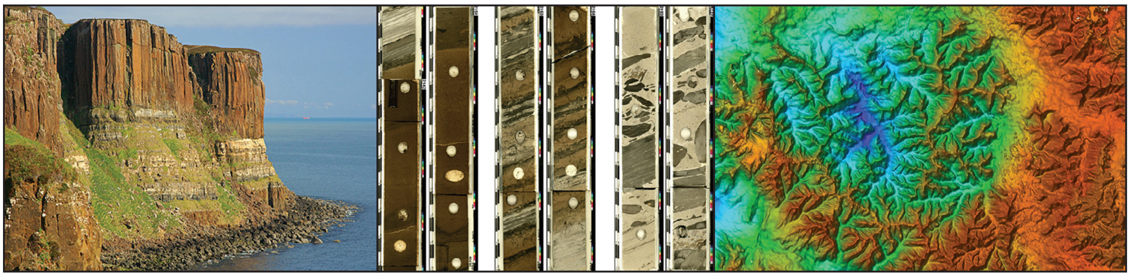
Call for Abstracts – Deadline: 31 January 2020

New learning from exploration and development in the UKCS Atlantic Margin

20-22 May 2020

Robert Gordon University, Aberdeen



The UK Atlantic margin, including the West of Shetlands area, is the location of the UK's largest remaining hydrocarbon reserves, the largest recent field development investments and holds the greatest potential for future material discoveries in the UK.

In the 10 years since the last Geological Society conference on this region, great advances have been made in the understanding of its diverse plays, from fractured basement to Eocene coastal deposits, and everything in between.

This three day meeting gives a unique opportunity to learn about the geoscience of recent discoveries and field developments, as well as how technology is developing to meet the imaging and drilling challenges of the area. For a fully immersive experience, there is an opportunity to see the diverse range of reservoirs in outcrop on the Isle of Skye (15-17 May) and in core at the Iron Mountain facility at Dyce (19 May).

Associated events:

- Three day field trip to the Isle of Skye run by Nick Schofield (Aberdeen University) and Stuart Archer (Nautilus RPS)
- Guided core viewing day at Iron Mountain (Dyce)
- Social programme to include a conference dinner.

Conference themes:

- Paleocene deep water reservoirs
- Mesozoic pre-, syn-, and post-rift plays
- Palaeozoic play (e.g. Carboniferous and Devonian at the Clair field)
- Non-clastic plays (e.g. fractured basement, volcanics, carbonates)
- Paleocene-Eocene volcanic-associated reservoirs
- Extra-UK Atlantic Margin
- Multidisciplinary technology session (e.g. advances in drilling techniques, sub-sill imaging, EOR)
- Geodynamics, basin modelling, thermal and uplift/subsidence history, migration routes
- What's next? The next 10 years for exploration and development in the region.

Call for Abstracts:

Please submit talk or poster abstract to sarah.woodcock@geolsoc.org.uk by 31 January 2020.

For further information please contact:

Sarah Woodcock, The Geological Society, Burlington House, Piccadilly, London W1J 0BG.
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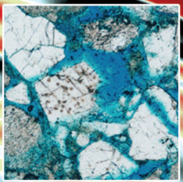

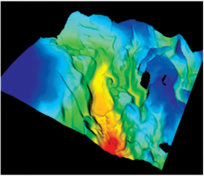

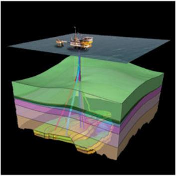

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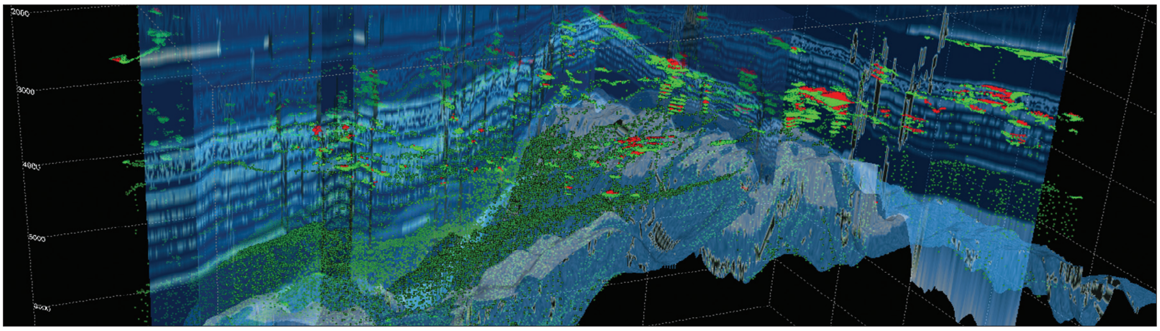
Call for Abstracts – Deadline: 10 April 2020

Basin and Petroleum Systems Modelling

Best Practices, Challenges and New Techniques

16-18 September 2020

The Geological Society, Burlington House, Piccadilly, London



The prediction of viable petroleum systems is critical to meet the growing energy demand. This meeting will discuss the importance of Basin and Petroleum System Modelling (BPSM) in petroleum systems evaluations, focussing on best practices, recent developments, and opportunities for the future.

New and improved digital capabilities have enabled a more integrated approach to petroleum system analysis; therefore, the impact of newly available data and technologies in BPSM will be reviewed. As the energy sector shifts from traditional hydrocarbon to alternatives, and new disciplines such as carbon capture and storage emerge, we will look at novel and innovative uses of BPSM.

Key Topics:

- **Best practices in different exploration scenarios:** mature, frontier, and unconventional areas
- **Effectiveness of modelling geological processes:** heat flow; erosion; kinetics; thermal conductivity
- **Charge and migration modelling**
- **New techniques in BSPM**
- **Integration with other disciplines:** carbon capture and storage; reservoir engineering; geothermal
- **Dealing with predicted risk and uncertainty**
- **Case studies**

The conference will bring together professionals from academia, government agencies, and industry to discuss BPSM through a series of presentations and panel discussions, suitable for both a specialist basin modeller and for a general exploration geologist. A dedicated student poster session will encourage participation from a new generation. The meeting will include an optional one-day field trip to the classic petroleum geology outcrops of Dorset.

Call for Abstracts:

Please submit talk or poster abstract to sarah.woodcock@geolsoc.org.uk by 10 April 2020.

For further information please contact:

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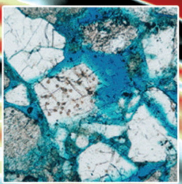

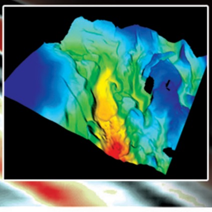

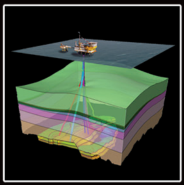

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Call for Abstracts – Deadline 29 February 2020

Development and Production Geology of Carbonate Reservoirs

28-29 October 2020

The Geological Society, Burlington House, Piccadilly, London

Carbonate reservoirs constitute some of the most important sources of global oil and gas production. They form the world's largest oil and gas accumulations, the world's highest-producing fields, and have some of the longest production histories. Significant new carbonate discoveries continue to be made, and carbonates are also a source of geothermal energy or may be utilised for gas storage.

Successful development of supergiant carbonate reservoirs can result in plateau production that may last for decades, giving high ultimate recovery factors. But, carbonate reservoirs can also be some of the most complex in terms of reservoir quality and heterogeneity. Many give disappointing ultimate recovery factors and some are deemed uncommercial with current technologies. Fundamental geological understanding, sufficient and appropriate geological and dynamic data, and the construction of effective models are the keys to optimising the exploitation of such reservoirs.

This conference will focus on how lessons learned from more than a century of discovery, appraisal and development of carbonate reservoirs may be applied to emerging discoveries. It will bring together the experiences of diverse operators with an objective of highlighting best practices for the geological characterization of carbonate reservoirs from appraisal to production.

Potential session themes:

- Excess permeability – blessing or curse?
- Pores vs stratigraphy – what controls dynamic reservoir behaviour?
- Reservoir analogues – how useful are they?
- Static modelling of carbonate reservoirs – how predictive can we be?
- Multiscale/multidisciplinary dynamic reservoir characterization – how can we integrate geology effectively?
- Improving recovery/revitalising old carbonate fields – adding value through geological understanding.

Planned field trips:

The Carboniferous platforms of Derbyshire, led by Pete Gutteridge, Cambridge Carbonates.
Zechstein carbonates of the north-east of England, led by Geospatial Research Ltd.

Call for Abstracts:

Please submit talk or poster abstract to sarah.woodcock@geolsoc.org.uk by 29 February 2020.

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Paul Wright
National Museum of Wales and Consultant

Trevor Burchette
Royal Holloway, University of London and CRG Ltd

Confirmed Keynotes:

Mishrif Formation reservoirs of Rumaila Field
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Pre-salt reservoirs of Lula Field
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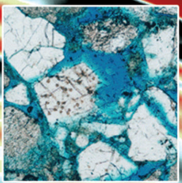
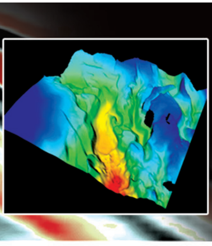
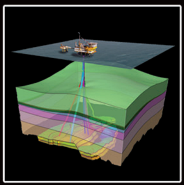

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Call for Abstracts - Deadline 20 December 2019

Core Values: the Role of Core in 21st Century Reservoir Characterisation

26-28 May 2020

The Geological Society, Burlington House, Piccadilly, London

Reynolds and Krevor 2015

Core has traditionally played a key role in the characterisation of conventional and unconventional hydrocarbon reservoirs, from exploration to mature production. It is the only means by which to observe and make measurements on actual reservoir rock. However, the recent oil industry downturn has driven many to question the value of taking core, due to the associated increased costs and potential risks to well operations. In tandem, advances in other reservoir visualisation techniques, such as seismic and borehole imaging, have been used to give weight to the contention that coring is an increasingly redundant means of characterising reservoirs.

Through four main themes this 3-day conference will aim to redress the balance in this debate by exploring the role core can, or should, play in the 21st century exploration to production cycle:

- Is core critical to sound commercial decision making?
- What are the challenges and benefits of integrating core-derived understanding across the geological, petrophysical and engineering spectrum?
- Integration of traditional core characterisation methods with new core, well and reservoir visualisation and mapping technologies - is the sum greater than its parts?
- How can the extensive network of global legacy core collections best be utilised to maximise their business and research worth?

Dedicated sessions will allow delegates to view core that has been central to addressing many key reservoir issues, under the direct guidance of those responsible for meeting such challenges. Speakers are thus invited to bring core to illustrate their presentation, and indicate if this is of interest when submitting an abstract.

For further information or submit an abstract:

Please submit abstract contributions to abstracts@geolsoc.org.uk and copy to sarah.woodcock@geolsoc.org.uk

For more information, please contact Sarah Woodcock, The Geological Society, Burlington House, Piccadilly, London W1J 0BG. Tel: +44 (0)20 7434 9944, sarah.woodcock@geolsoc.org.uk

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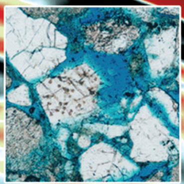

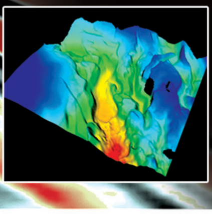

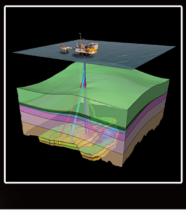

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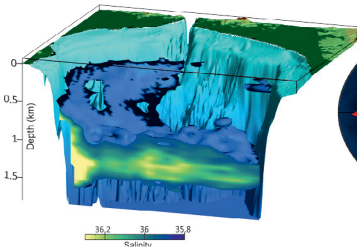
Call for Abstracts – Deadline: 30 June 2020

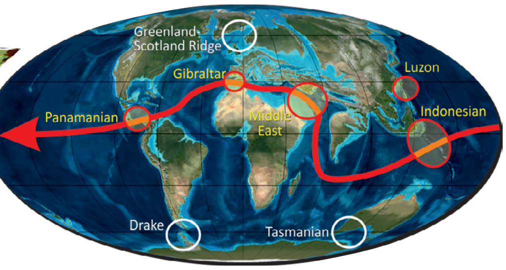
Oceanic Gateways:

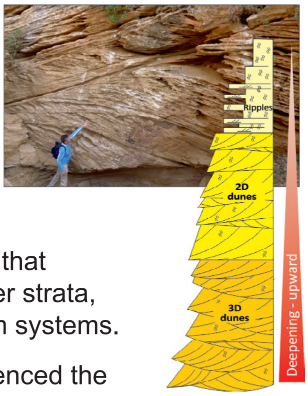
Modern and Ancient Analogs and their Conceptual and Economic Implications

28-30 September 2020

The Geological Society, Burlington House, Piccadilly, London







Ocean basins are connected by gateways representing narrow passages that control ocean circulation which in turn affects the distribution of deep-water strata, including various elements in existing and potential deep-water petroleum systems.

In the geological past, the onset and closure of palaeogateways has influenced the global ocean circulation, climate, distribution of biota, evolution/extinction events, evolution of basins, sedimentary processes and hydrocarbon source rock and reservoir distribution.

This three-day conference aims to bring together diverse experts working on modern and ancient gateways in order to improve our knowledge, models and predictive power. Sessions will include the following themes:

- Oceanographic / palaeoceanographic processes
- Tectonic controls on gateway geometry
- Sedimentary processes and deposits within and around gateways
- Data integration & multidisciplinary analysis
- Implications of gateways and contourite deposits for hydrocarbon exploration.

Oceanographers, paleoceanographers, geomorphologists, sedimentologists, marine geologists, geologists as well as petroleum geologists and researchers working in numerical modelling and plate tectonic reconstructions are all invited to join the conference.

Call for Abstracts:

Please submit talk or poster abstract to sarah.woodcock@geolsoc.org.uk by 30 June 2020.

For further information please contact:

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